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ASSOCIATE COMMITTEE ON HYDROLOGY
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PROCEEDINGS OF THE CANADIAN HYDROLOGY SYMPOSIUM No 17 - 1988

Canadian Research Basins: Successes, Failures and Future

COMPTES RENDUS DU SYMPOSIUM CANADIEN D'HYDROLOGIE No 17 - 1988

Les Bassins de Recherche canadiens: Succès, Eches et Futur

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FOREWORD

The 17th Canadian Hydrology Symposium was held on May 9-11, 1988, at the Banff Centre, Banff, Alberta, under the auspices of the National Research Council of Canada's Associate Committee on Hydrology. This symposium brought together most of those who have been involved in research in or management of Canada's Research Basin Program. These proceedings contain two distinct types of papers:

- Reviews of particular research basins.
- Reports on research conducted in conjunction with a research basin.

The review papers were solicited by the program committee in order to provide a written record of the many research basins that exist across Canada. Research papers were voluntary. The papers contained herein have been retyped, with minimal editing and printed essentially as they were received, without referee review. A special word of thanks goes to Pierre Bernier for his translation of most of the abstracts to French.

I wish to thank the following people whose efforts made this symposium a reality. The program committee consisted of Dave Daugharty, Eugene Hetherington, Bob Swanson and Trevor Dickinson (Chairman). Local arrangements were handled by Ron Deeprose and Judy Lindsay.

AVANT-PROPOS

Le 17^{ième} Symposium Canadien d'Hydrologie s'est déroulé au "Banff Centre", Banff, Alberta, du 9 au 11 mai 1988, sous les auspices du Comité Associé sur l'Hydrologie du Conseil National de Recherches du Canada. Ce symposium rassemblait la plupart des personnes qui ont été impliquées dans les aspects de recherche ou de gestion du Programme Canadien de Bassins de Recherches. Ce compte-rendu contient deux types de communications:

- Les synthèses sur des bassins de recherches particuliers.
- Les présentations de résultats de recherches menées sur un bassin.

Les synthèses étaient toutes des communications invitées. Le comité du programme tenait ainsi à obtenir un compte-rendu écrit sur les activités de tous les bassins de recherches au Canada. Les communications de recherche étaient volontaires. Les communications contenues dans ce compte-rendu ont été mises en page avec peu d'édition, et ont été imprimées essentiellement comme reçues des auteurs, sans comité de lecture. La traduction au français des résumés et autres textes a été réalisée par Pierre Y. Bernier.

Je désire remercier les personnes qui ont rendu cette rencontre possible. Le comité du programme était composé de Dave Daugharty, Eugene Hetherington, Bob Swanson et Trevor Dickinson (Président). Les arrangements locaux ont été organisés par Ron Deeprose et Judy Lindsay.

R.H. Swanson
General Chairman/Président Général
Canadian Hydrology Symposium - 88/Symposium Canadien d'Hydrologie -88

PRÉFACE

En 1964, le Comité Associé sur l'Hydrologie du Conseil National de Recherches tenait un symposium sur les "bassins de recherches"[1], similaire à celui-ci, à Guelph en Ontario. Dans son allocution d'ouverture, le Dr. R.H. Clark demandait:

> La valeur de cette approche [des bassins de recherches] est-elle suffisante pour justifier l'investissement de tels montants et de tels efforts sur de si longues périodes?

Un des principaux objectifs de cette rencontre-ci sur la révision des bassins de recherches est justement de répondre à cette question.

La majorité d'entre nous qui oeuvrons en hydrologie voulons des données. Est-ce que la quantité, qualité et la pertinence des données récoltées par le programme canadien de bassins de recherches a su justifier son existence? En général, oui, malgré que le besoin en données hydrométéorologiques nouvelles sera toujours là. Mais ce besoin est sans doute moins impérieux qu'en 1964 car le programme a fourni une abondance de données sur l'hydrologie de régions, et sur les différences hydrologiques entre régions.

La majorité d'entre nous désirent une meilleure qualification du personnel. Le programme canadien de bassins de recherches a-t'il mis à la disposition des organismes responsables des ressources en eau du personnel compétent? Ces personnes utilisent-t'elles leur expertise ou ont-t'elles été détournées vers des postes administratifs? Nous pouvons sans doute dire que le besoin en hydrologistes qualifiés sera toujours là. Un des résultats du programme canadien de bassins de recherches est le grand nombre de personnes qui se disent hydrologistes.

Est-ce que nous, les hydrologistes, nous appliquons dans notre travail ce que nous avons appris grâce au programme canadien de bassins de recherches? L'étendue du Canada, la diversité de sa topographie, de son climat et de son hydrographie nous masquent souvent le fait que les principes hydrologiques de base sont les mêmes partout. Il pleut ou il neige; la transpiration des plantes transfère de l'eau du sol à l'atmosphère; l'évaporation s'effectue à partir de l'eau à la surface de la végétation, du sol, des lacs et des rivières; les eaux de surface et souterraines se drainent dans des cours d'eau coulant vers les océans d'où provient l'eau pour la pluie et la neige. Ces éléments sont connus, et la plupart d'entre nous qui avons été formés en hydrologie possédons suffisamment de connaissances ou d'expérience pour estimer l'effet d'un de ces processus sur le régime et la quantité d'écoulement d'un bassin. Appliquons nous cette compréhension du système à la gestion des ressources hydriques ou au choix d'activités de recherche?

La question du Dr. Clark restera sans doute toujours sans réponse. La valeur du programme canadien de bassins de recherches vient de ce que nous en avons appris, du degré d'application de ces connaissances à la gestion des ressources hydriques, et de ce que nous pouvons éviter de répéter suite au programme. Nous devons nous servir de l'expérience et des données acquises à la fois comme base et comme point de départ pour les activités en hydrologie.

R.H Swanson
Président Général
Symposium Canadien d'Hydrologie - 88

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[1] Compte-rendu du Symposium d'Hydrologie No.4, tenu au Ontario Agricultural College, Université de Guelph, les 27 et 28 mai 1964.

PREFACE

In 1964, the National Research Council's Associate Committee on Hydrology held a symposium on "Research Watersheds"[1] at Guelph, Ontario, somewhat similar to this one. In his opening address to that symposium, Dr. R.H. Clark asked the question:

> Is the value of this approach [watershed research] sufficient to justify large expenditures of manpower and money over a considerable length of time?

To a large extent, one of the principal objectives of this present symposium to review research basins was to answer that question.

Most of us who work in the broad field of hydrology want more data. Has the amount, quality and representativeness of the data collected justified Canada's research basin program. To some degree, yes. But, there will always be a need for hydrometeorological data that we do not have. That need is probably not so overwhelming now as it was in 1964. Canada's research basin program has provided a wealth of data, both on the hydrology of local areas, and on the variation that one can expect between regions.

Most of us want more training. Has Canada's research basin program provided water resources agencies with a pool of talent from which to draw? Are those who have been trained using their expertise, or have they been diverted to administrative positions? One can always argue that there will always be a need for educated (trained?) hydrologists. One legacy of Canada's research basin program is a large number of people who call themselves hydrologists.

Are we, who call ourselves hydrologists, applying what we have learned by our participation in Canada's research basin program? The vastness of Canada, its diversity of topography, climate and hydrography tends to overwhelm us and to divert our attention from the commonality of the functioning of hydrologic processes. Rain and snow falls; vegetation takes up water from the soil and discharges it into the atmosphere; evaporation occurs from the surface of vegetation, the soil, lakes, and rivers; surface and subsurface waters flow together into streams and eventually to the oceans from which the water for rain and snow originated. We know these things and most of us, who have been trained in hydrology, have sufficient experience, understanding or knowledge to estimate both the time pattern and quantities involved in order to describe the effect of at least one process on the overall water balance of a watershed. Do we apply this understanding to the management of our water resources or to guide us in our selection of new research activities?

There probably never will be a final answer to Dr. Clark's question. The worth of Canada's research basin program must be justified by what we have learned from it, to what degree we apply the data and knowledge gained to manage our water resources, and what we can avoid repeating as a result of it. We must build both from, and on, the data and experience that this program has provided.

R. H. Swanson
General Chairman
Canadian Hydrology Symposium - 88

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[1] Proceedings of Hydrology Symposium No.4, Held at Ontario Agricultural College, University of Guelph, on 27 and 28 May 1964.

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SECTION I

BASIN REVIEWS

CANADIAN HYDROLOGY SYMPOSIUM (CHS:88)
ASSOCIATE COMMITTEE ON HYDROLOGY
NATIONAL RESEARCH COUNCIL OF CANADA
MAY 9-11, 1988
BANFF, ALBERTA

CHS
88
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SYMPOSIUM CANADIEN D'HYDROLOGIE (SCH:88)
COMITÉ ASSOCIÉ D'HYDROLOGIE
CONSEIL NATIONAL DE RECHERCHES CANADA
LES 9-11 MAI 1988
BANFF, ALBERTA

Canadian Research Basins - in review

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ABSTRACT The Canadian Hydrology Symposium, CHS-88, held at Banff, Alberta, in May 1988, provided a forum for discussion of the findings, failures and the future of the Canadian research basin program. Fifty three oral or poster papers were presented and are published in its proceedings. Their authors addressed several specific questions with respect to the reasons for, and the findings of, basin research programs. These presentations provide useful information and guidelines for water managers, water program administrators and water resources researchers for the establishment, interpretation and evaluation of research basins.

Reductions in funding and support have made it relatively evident that water managers and administrators are somewhat disillusioned with research basin programs. We see this lack of support as symptomatic of two causes; unrealistic expectations on the part of many administrators and inadequate application of hydrologic knowledge by scientists to the solution of problems.

The focus of many early research basin projects was apparently not on problems, but on data. More recent efforts have focused interdisciplinary teams on the resolution of problems. These later efforts appear to be having a greater impact on water resources management.

One of the primary benefits of the Canadian research basin program has undoubtedly been the education of numerous students and scientists, which would not have occurred in its absence. We recommend that this educational aspect be formalized and strengthened. We have also listed a number of recommendations for the establishment and operation of both educational and research basin programs, that we feel would make future programs more effective if followed.

The Canadian research basin program has provided a wealth of hydrologic data and numerous scientific publications. However, it will not be seen as a success unless future basin programs result in a more integrated approach to research, that leans heavily on the confirmation and testing of existing understanding of hydrologic processes, and the application of findings to solve water related problems. Unfortunately, basins are still being established that do not meet these fundamental requirements.

RÉSUMÉ Le Symposium Canadien d'Hydrologie, SCH-88, tenu à Banff, Alberta en mai 1988, a servi de forum où se sont discuté les succès, les échecs et le futur du programme canadien de bassins de recherche. Le compte-rendu contient le texte des 53 communications écrites ou orales qui y ont été présentées. Les auteurs ont abordé plusieurs points spécifiques touchant les

raisons-d'être et les résultats de programmes de recherche sur bassin. L'information et les directives contenues dans ces textes peuvent servir aux gestionnaires et aux chercheurs dans la mise en place, l'interprétation et l'évaluation de bassins de recherche.

Les réductions en supports financier et autres font bien voir le désappointement des gestionnaires et administrateurs de la ressource hydrique face au programme des bassins de recherche. Nous croyons que ce fléchissement de support a deux sources: les attentes non- réalistes de la part de plusieurs administrateurs, et la faible utilisation des connaissances hydrologiques par les scientifiques pour solutionner des problèmes.

Plusieurs des programmes initiaux ont porté leur attention non pas sur un problème, mais sur l'acquisition de données. Les programmes plus récents ont souvent concentré un effort multidisciplinaire sur un problème spécifique. Ces derniers projets semblent avoir un plus grand impact sur la gestion de l'eau.

Un des bénéfices directs du programme canadien de bassins de recherche a sans doute été la formation de nombreux étudiants et scientifiques, ce qui ne se serait pas produit sans le programme. Nous recommandons que cet aspect éducationnel soit formalisé et reconnu. Nous avons aussi inclus une liste de recommandations pour la mise en place et l'opération de programmes avec bassin pour fins éducative ou de recherche. Nous croyons que ces recommandations rendraient de tels programmes plus efficaces.

Le programme canadien de bassins de recherche a généré des données hydrologiques et des publications de grande valeur. Cependant, le programme ne sera perçu comme étant un succès que si les programmes à venir entraînent une approche plus intégrée de la recherche, basée sur la validation des connaissances sur les processus hydrologiques, et sur l'application des résultats dans la résolution de problèmes se rapportant à l'eau. Malheureusement, on met encore sur pied des programmes qui ne répondent pas encore à ces exigences.

INTRODUCTION

Research basins have been a focus for hydrological activities in Canada for more than 25 years. Many basins have been established. Some have quietly disappeared without published record of objectives or observations. Others have seen continual and expanding activity leading to a multitude of results and recommendations.

The purpose of Canadian Hydrology Symposium - 88 was to provide a forum for discussion of findings, failures and the future of hydrological research programs. A stated intent was that the published proceedings would provide useful information - perhaps even some guidelines - for water managers, water program administrators and water resources researchers for the establishment, interpretation and evaluation of research basins. Much food for thought is contained in the 53 papers assembled from the oral and poster presentations, as they have addressed the following pertinent questions.

(a) What prompted the original research?
(b) Why was the research basins approach chosen; and why the particular basin(s)?
(c) What topics have been researched in the basin(s)?
(d) Where studies have been completed, how have the results impacted the understanding or management of water resources in Canada?
(e) Are significant research findings available or being used by other researchers and water resource managers? If not, why not?

(f) Should the research basin approach be used again, or should things be done differently (What? How?), if the same problems were to arise?

It is neither possible nor appropriate to provide a comprehensive summary of all the symposium material. As we have listened to the answers to the questions and viewed the poster presentations, we have sought to gain an insight into the worth of research basin programs. With this in mind, we present a summary of the answers to the specific questions, a discussion of some problems that were implied but not expressly stated, and our recommendations for future basin programs.

SPECIFIC ANSWERS TO THE QUESTIONS

What prompted the research?

The papers presented and the discussion of them revealed that a large majority of Canadian research basin studies, and virtually all of such studies initiated before 1980 (including the IHD basin program), were prompted by a desire for hydrologic knowledge and data. Basin after basin was established to obtain a data set for and learn about a representative regime e.g. the Maritimes, Ontario and Quebec, the Prairies, the West Coast, and the Arctic; wetlands, drylands, glaciers, virgin areas, forested regions, and agricultural lands. So-called experimental watersheds were also initiated to monitor impacts of either urbanization or timber harvesting primarily on water yield. And although these watersheds were established in response to concerns about man's influence on the hydrologic system, the driving force was one of learning about that system.

The original intent of the early basin studies was to collect data, and for the most part, new hydrologic knowledge was expected to follow automatically from those data. A few basins were set up to explore the extrapolation of results through spatial scales, or to develop and investigate the implications of watershed models.

More recently, since the mid 1970's, perhaps having had a chance to learn about the local hydrological system from earlier studies and/or having to operate in a much tighter economic climate, hydrologic managers and researchers have established basin projects to solve problems. Whether these relate to soil erosion, nonpoint source pollution, phosphorus and pesticide transport, acid rain, or flooding and other water management issues, such problems and the need for their solutions provided the justification for basin studies. It is interesting to note that the problem-prompted research basin studies have almost unanimously been of shorter duration and have involved more researchers on a wider range of topics than the basin studies driven by curiosity.

One or two studies identified educational needs as being fundamental to the establishment of a research basin, and one noted public relations or visibility. The apparent lack of attention initially given to these areas is particularly curious in light of the program impacts and suggestions regarding future basin research discussed later.

Why the basin approach - and why these basins?

In most of the basin projects it would appear that it was deemed unnecessary to develop a rationale for taking a research basin approach. Some of the papers have suggested that "basins had been useful in the U.S.", watershed projects "were in vogue", and research basins represented a "state-of-the-art approach" or "the approach of the time". However, a number of researchers have identified the watershed as a fundamental hydrologic and geomorphic unit, one which integrates many important processes and effects and one from which it is possible to extrapolate results. The watershed is also quite desirable because of the zero flux boundary condition, almost always realized with regard to surface flows (an exception being some of the Arctic basins), and often realized (although usually assumed rather than validated) with regard to subsurface flows.

The reasons offered for the selection of specific research watersheds perhaps reflect most clearly those criteria considered to be most important for basin selection.

(a) The watershed was representative of the hydrologic regime of interest and of the problem(s) being addressed (where such had been identified).

(b) The watershed was accessible, convenient and available.

(c) The chances of land use changes and/or physical and biological disturbances were considered to be minimal in time and over the area, or the basin's researchers had control over changes or were closely in touch with change agents.

(d) There were already some valuable background data available for the watershed.

(e) The watershed was reasonably safe from vandalism.

(f) The watershed had good definition (i.e. the watershed divide was clearly definable).

(g) Stable gauging sites were available and easily instrumented and monitored.

(h) There was considerable local interest in the area.

Topics explored

The range of topics explored in Canadian research basins is extensive and is only summarized here. The evolution of the topics over the some 30 years of studies and the approaches taken to explore the topics are noteworthy.

In the research basins established in the 1960s, when the principal interest was gathering some data and learning about some of the hydrologic regimes, topics focused on the basic water quantity components of the hydrologic cycle (i.e. precipitation, streamflow, evapotranspiration). Where a concern such as urbanization or timber harvesting existed, particular attention was also given to the land use patterns. Moving into the 1970s, the spatial variability of a number of the variables and processes (most notably, precipitation and soil moisture storage) received more attention; and water quality began to be of interest, particularly as it involved soil erosion and sediment yield. Later in the 1970s and on through the 1980s, water quality, environmental and ecological topics were more in vogue, as basin settings were seen to be prime locations to resolve environmental issues relating to amounts, sources, and transport paths of many contaminants.

Although the initial approach taken to most research basins was essentially one of collecting data and of focusing on watershed scale studies, increasingly the basins became outdoor laboratories for a host of studies ranging from the microscale through plot and hillslope scales to the watershed scale. In fact some of the most significant results have been achieved when studies from the various scales have been integrated, a modelling approach usually providing a framework for that integration.

Problems!

Perhaps one of the most significant outputs from the Canadian research basin experience is a list of the problems cited! Certainly, this is a valuable reference for researchers and research managers to ponder when contemplating the establishment of a research watershed. The most-cited problems have been grouped below in four classes:

Technical and Practical Problems:

(a) Instrument breakdowns (more prevalent in the earlier years with older designs).

(b) Insufficient sampling to ascertain temporal variations.

(c) Practical problems associated with instrument installation.

(d) Requirement for and difficulties with road construction and maintenance.

(e) Inclement and extreme weather conditions (affecting or even incapacitating instruments; making measurements difficult or impossible).

(f) Unstable gauge locations.

(g) Vandalism.

(h) Insufficient servicing of instruments (due to weather conditions or remoteness).

Data Management and Analysis Matters:

(a) Lack of continuous data (due to instrument and/or human failures).

(b) Lack of a central data repository (data for different variables and studies residing with different agencies and persons).

(c) Lack of quality control.

(d) Too much time on data collection and not enough time on analysis.

(e) Too much time on detailed studies and not enough time on integration of results.

(f) Too much time on setting up and "playing" with models and not enough time on interpretation and extrapolation of results.

Financial and Personnel Resource Problems:

(a) Lack of sufficient funds and a commitment for ongoing funding (often caused by a lack of awareness of the real costs, resulting in too short a study or the waste of time and energy striving for more funds).

(b) Lack of a full-time coordinator (deemed by many in hind sight to be a necessity).

Management Issues:

(a) Lack of a long-range plan which is focused yet flexible (leading to a lack of direction, the collection of unusable or un-needed data, and the failure to collect necessary data).

(b) Lack of ongoing commitment to the project, with shifting agency priorities (affecting the allocation and commitment of funds and personnel).

(c) Lack of ongoing coordination (staff turnovers leading to a lack of continuity and commitment).

(d) Lack of awareness of issues being addressed and problems being encountered.

Impact of Results

Despite the many problems encountered in the research basins, there have been substantial results and their impact has been varied, extensive and often of a different nature than originally anticipated. Scientific results were anticipated, and there is little doubt that the understanding of hydrologic regimes both particular to Canada and more widespread has been expanded as a result of basin studies and the subsequent publication of innumerable papers and reports. There is also no question that Canadian research basins have played a major educational role, despite the fact that in most cases education was not initially identified as a prime objective. A great number of graduate and undergraduate university and college students have benefited from the opportunity to conduct research studies in the basins, make use of basin data, and use the basins as outdoor learning laboratories.

Perhaps more particularly, the research results from the more recently established research basin projects, which have focused on environmental issues, have begun to have an impact on the establishment of water resources management policy and guidelines and on their implementation. This impact has been the result of, and has led to, increased and improved cooperation amongst not only hydrologic researchers but also government agencies and the university community. There has also been an increased awareness of the significance of hydrology on the part of agencies and lay persons, perhaps due in large part to the informal transfer of information and results among groups of individuals. The knowledge gained about how to organize and run research basins in order to maximize their impact may have been as useful as the advances in scientific knowledge.

Would you do it again?

A large majority of the symposium participants endorsed the research basin approach to acquire hydrological knowledge, to resolve environmental issues, and to educate students, water resource managers and the laity. However, a number of bad experiences have discouraged some researchers from being supportive of further basin projects. For example, it has been stated that the basin research is too costly for what is achieved; we simply don't need basin-type data any more; and unless water and other resource managers are sufficiently committed to the research exercise, the likelihood of results being used for management decisions is minimal.

IMPLIED PROBLEMS WITH RESEARCH BASINS

As we listened to the oral presentations and viewed the posters it became obvious to us that there were some underlying concerns that were not being addressed directly in the papers. These are discussed briefly below.

Research basins have been used as an excuse to avoid action.

Traditionally research basin programs have been established to study within a particular discipline or land area over a time period of 15 to 25 years or more. In some cases the solution to the prompting problem or a conclusion to the stated hypothesis already existed. For instance, many studies have demonstrated that most erosion and sedimentation problems associated with timber harvest are a result of poor road construction, particularly near stream crossings. The reason often offered for establishing a research basin to study this problem, rather than an action plan to resolve it was; "it has not been done in [this place], therefore we don't know if it will work here". It seems remarkable that many scientists and managers are unwilling to attempt to interpret or integrate research results from other places to solve local problems!

Some of the papers in these proceedings report the use of the HSPF hydrologic model or of the WRENSS procedure as aids in instrumenting and interpreting the results from research basins. Those doing so are to be commended. However, research basins are still being established, apparently without even an attempt to use the available tools first. This problem may be alleviated if we provide easier to use models and techniques to interpret and extrapolate hydrologic knowledge, but better models are not of much use to those who refuse to try them, or who do not have an adequate scientific background to apply them!

The results have not been communicated in a way that receives the attention of managers.

Most of the IHD basin projects generated a long list of scientific publications, which is commendable. While these publications may be of use to other researchers, they are often ignored or not understood by managers. The scientific results are not usually presented in a form or format that is useful to the hydrologic manager. More effort must be put into interpretation and extension of results so that the managers can see their usefulness in the solution of local hydrologic problems.

The research was done primarily in response to scientific curiosity, rather than to a hydrologic problem.

Most research basin projects need a defined application goal in order to maintain continuing support by water managers and research administrators. Scientists, on the other hand, often wish to develop research projects to satisfy their curiosity. Some curiosity-driven research is necessary if the science of hydrology, as opposed to the applied art of hydrology, is to be furthered. However, rightly or wrongly, curiosity driven research must, at present, be conducted as a side line within projects with well defined and accepted application goals.

The solution to a problem found through research basin efforts does not coincide with nor justify current operations.

In some cases, those managers originally supporting a particular piece of research really wanted a "blessing" of their present management rather than an answer to the problem. When the results did not coincide with this expectation, they were ignored. There is not much that those establishing a research basin program can do about this problem except to get a firm commitment by users prior to initiating the research to resolve the problem, even if it might require a change in their operations.

Research efforts should not be stifled by preconceived and unrealistic time tables.

The time scale for the variations in climate that any research basin undergoes is a fair estimate of the time needed to properly conduct an experiment that involves the hydrological characteristics of a basin. If the basin is to elucidate processes within the hydrologic system, then the desired range of climatic variation that affects the processes ought to be allowed to occur. For example, it would be ludicrous to establish a research basin with a goal to investigate the effect of climatic change on streamflow, and then to curtail data collection before the climatic change occurs.

Likewise, experimental techniques should be used that are appropriate to the solution of the problem in mind, or to the research objective. A research basin approach will not always be the appropriate tool to solve a given hydrological problem. Unfortunately, the IHD research basin program may have inadvertently focused research on "interesting" scientific problems within research basins, simply because they were convenient and existed, rather than on the solution of the true hydrologic problem that the research was supposed to address.

DISCUSSION

In light of a reluctance among both scientists and managers to interpret and use research findings, how are we to make progress in the application of hydrologic information to the solution of current and local problems? Are research basins the best approach? Must each new situation spawn a research project that almost always delays implementation of remedial measures, often past the point where they can be taken?

The papers presented at this symposium shed some light on these questions. It is rather clear that the educational benefit of research basins far exceeds that of textbooks and publications. Some of the researchers who have worked in research basins have become disenchanted with research basins although most now view them from a different perspective than the rather simplistic viewpoint as a source of hydrologic data. This educational process could not have occurred in the absence of the Canadian basin program. Research basins have thus established themselves as a most necessary part of any hydrologic program.

Is the price that Canada has paid for such an education too high? Not if it results in better management and understanding of our water resource. What must follow from Canada's research basin program is a more integrated program of research and application. We see this already beginning to happen where a pressing environmental issue, acid rain, has forced researchers to use their best tools and joint knowledge to find a way to solve, or at least to mitigate the effects of, this problem. Similar integrated and joint efforts will probably have to be mounted with respect to soil salinity, agricultural and forestry chemicals, and climate change, to mention just a few of the current issues facing Canadian hydrologists.

The most depressing aspect of this symposium was to find that there are still researchers who have not learned from their experience. Although the hydrologic cycle is complex, it is not incomprehensible. Those who seek simplistic solutions to hydrologic problems are doomed for defeat and disappointment. Surely it should be obvious by now that although individual watersheds are unique, the hydrologic processes that occur on any watershed are common to all watersheds!

If research basins continue to be established simply to "determine if [some action] causes a change in [quantity, quality, regime] of streamflow", then Canada's program over the past 25 years must be viewed as a failure! Research basins are much too costly and time is too valuable to be wasted in this manner. They must be used as places to test and/or verify our understanding of the hydrologic system, to increase our ability to integrate the action and interaction of various hydrologic processes, and to predict the hydrologic consequences of human or climatic perturbations of those processes wherever they are encountered. If those of us who have been fortunate enough to participate in Canada's research basin program refuse to use the scientific tools at our disposal to answer scientific questions, then how can we expect those further from the science (i.e. managers) to ever use these tools?

RECOMMENDATIONS

Whether the research basin approach was endorsed or attacked, there have been numerous recommendations offered for those contemplating future basin projects. The educational benefit cited by almost all leads us to recommend that a category of educational-research basins be established with teaching and student involvement as their primary reason for being. There should be a number of these and at least one should be located sufficiently close to each university so that appropriate faculty members at each Canadian university would be able to use both the data and facility in a routine manner. The following list, combined with that generated on problems, forms a set of guidelines for research (R) and educational (E) basins:

(a) All research basin programs should incorporate a multidisciplinary approach, including extensive monitoring of both water quantity and water quality variables. (E,R)

(b) An integrated study approach should be used, the plan taking advantage of individual but coordinated studies at the microscale, on plots, and over the watershed. (E,R)

(c) Until the present political and economic climate changes, research basins should be planned to be concentrated projects in 3 to 5 year blocks of time. (R)

(d) Regardless of time constraints, any proposal for a new research basin intended to supply information to solve a local water management problem (as opposed to a basin that is to be used primarily for educational purposes), should be scrutinized for evidence that existing hydrologic understanding and/or models have been tested and found to be deficient for proposing solutions to that problem. These deficiencies should be thoroughly examined to ascertain what information the basin's program must supply in order to correct them and to expedite a solution to the problem. (R)

(e) Research or educational projects should be planned and carried out within an existing basin wherever possible in order to make maximum use of available data. (E,R)

(f) Research basin plans should include public involvement and high visibility programs e.g. demonstrations, workshops, update meetings, etc., to raise the awareness and the profile of the research, and to maximize information exchange and the likelihood of use of results. (E,R)

(g) Management/operation of a research basin should include a cooperative and highly involved team. (E,R)

(h) In cases where a number of agencies are involved, it is imperative that financial and jurisdictional commitments be clarified at the outset, that a lead agency be identified, and that a full-time coordinator be appointed. (E,R)

(i) It is vital that a research basin program be coordinated with affiliated research, management and education programs. (E,R)

(j) The most up-to-date sensing and recording instruments, security systems, and quality control facilities should be used. (E,R)

(k) A data archiving and compilation system must be established at the outset and all data processed and verified as soon as it is received. (E,R)

(l) A permanent and secure field camp should be established. (E,R)

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Canada's benchmark basin program

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ABSTRACT Canada's benchmark basin program was established as part of the International Hydrological Decade (IHD) in 1966. The motivation for establishing this program reflected the concern that the past century had been a period of vast agricultural and industrial development in many areas of the world and that there were few gauging stations with a homogeneous record. The program objective was to provide a long term data base on the hydrological and climatological regimes of natural basins, which were to be kept free from the influences of man. By the end of the IHD in 1974, thirteen basins across Canada had been selected as benchmark basins. Instrumentation at these basins varied from having fairly complete climatological and hydrometric measurements at some basins to having only water level measurements at others. Unfortunately, maintaining such a long term program proved to be difficult and the continuity of the program has been disappointing. With recent concerns about climate change and global variability, there are renewed interests for this type of program. This paper reviews the benchmark basin program and examines its results and problems in Canada.

RÉSUMÉ Le programme canadien de bassins repères a commencé en 1966, comme participation à la décade hydrologique internationale (DHI). La motivation quantà l'établissement de ce programme reflétait la préoccupation que dans le siècle précédent, on avait connu une période de développement agricóle et industriel à grande échelle, dans nombreuses régions du monde, et qu'il y avait peu de stations ayant un dossier de relevés homogène. L' objectif du programmeé tait de fournir une base de données à long terme, pour la description des régimes climatologiques et hydrologiques des bassins naturels, que l'on devait garder à l'abri de l'influence des humains. À la fin de la DHI, en 1974, on avait sélectionné à travers le Canada, treize bassins repères. L'instrumentation allait de l'installation pratiquement complète pour les mosures climatologiques et hydrométriques à certains bassins, jusqu'à la plus simple, à d'autres bassins, où seul le niveau d'eau était mesuré. Malheureusement, il a été difficile de maintenir un tel programme à long terme, et on a été désappointé par sa continuité. Mais on a manifesté récemment des inquiétudes quant au changement climatique et à la variabilité globale; ce qui a renouvelé l'intérêt quant à ce type de programme. Cet article revoit le programme des bassins repères et examine ses résultats et ses problèmes au Canada.

INTRODUCTION

The concept of benchmark basins dates back to the 1960's. The WMO Guide to Hydrometeorological Practices (1965) recommended that:

- Each country and each natural region of large countries should contain one benchmark station to provide a continuing series of consistent observations on hydrological and related climatological data.
- Hydrological benchmarks should be established in areas relatively uninfluenced by past or future artificial changes.
- Since long-term records are the essence of a benchmark station, consideration should be given to existing stations if they meet the requirements.

These recommendations were motivated by several concerns. Among them was the fact that the hydrology of a region has been most directly and significantly influenced by man and in the past century man has been responsible for vast agricultural and industrial developments around the world. Yet there were very few long term gauging stations with homogeneous records to provide baseline comparisons between natural changes and artificial changes in hydrological regimes.

The objective of the WMO recommendations was to encourage its member countries to establish benchmark basin programs with the hope that eventually, long term data sets on the hydrological and climatological regimes of natural basins would result. Although the specific uses of these long term data sets were not fully conceived at the initiation of these programs, several general applications were suggested. The basic application was as a reference for detecting changes in the hydrological regimes of catchments which have been developed for use, but in addition, these data sets could be used in studies on the hydrological structure of natural catchments and the statistical structure of hydrological time series.

Langbein (1968) prepared a report which further explained the WMO recommendations and provided suggestions on the implementation of benchmark basin programs. He suggested that it was more desirable to expend the available funds on the collection of a moderate amount of data at many sites rather than concentrating the money and effort on a few sites with intensive data programs. He argued that the minimum useful data to be collected would be streamflow and precipitation. In Canada, however, air temperature for snowmelt estimation would be also be a basic requirement. In addition to the continuous or regular observations, fixed basin characteristics such as topography, geology, soil and vegetation should also be surveyed. He cautioned on the tendency in focusing all attention on point observations when it is the whole instrumented catchment that constitutes the benchmark. There was also a tendency to emphasize water quantity whereas water quality is becoming a dominant problem in many catchments.

THE CANADIAN PROGRAM

The Canadian benchmark basin program was established as part of the International Hydrological Decade (IHD) which was from 1965 to 1974. The program was co-ordinated by the Inland Waters Directorate (IWD) and the Atmospheric Environment Service (AES), with IWD being the lead agency. Planning and site reconnaissance began in 1966 and by 1970, thirteen benchmark basins had been identified and instrumented.

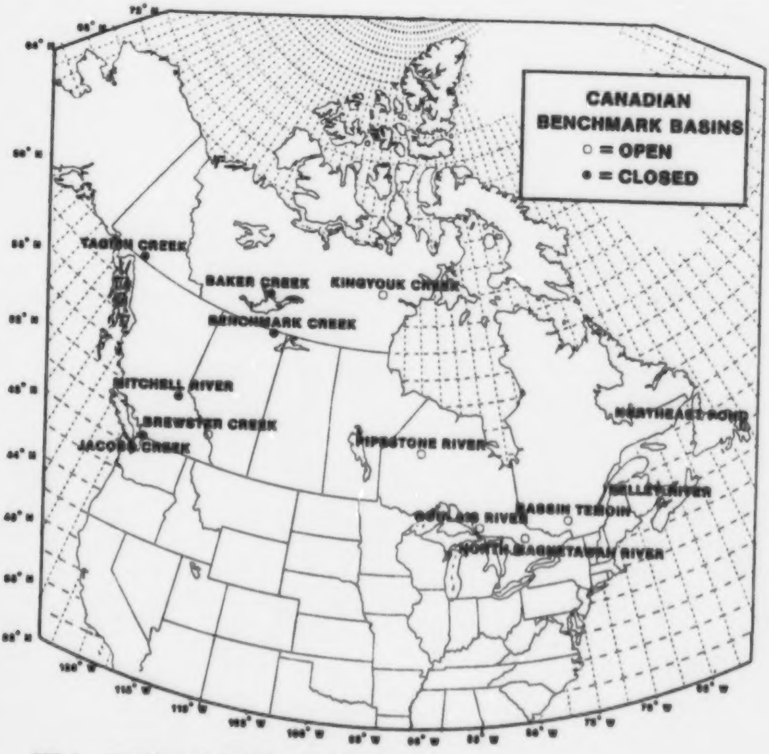
CANADIAN
BENCHMARK BASINS
○ = OPEN
● = CLOSED
BAKER CREEK
KINGVOUK CREEK
BENCHMARK CREEK
MITCHELL RIVER
BREWSTER CREEK
JACOBS CREEK
PIPESTONE RIVER
NORTHEAST POND
NORTH MAGNETAWAN RIVER

FIG.1 Location of Canadian benchmark basins.

These thirteen basins were located across Canada and covered all regions with the exception of Saskatchewan and Manitoba (Fig.1). They ranged in size from 4 km^2 to 6000 km^2 in area. Table 1 summarizes the current status of the Canadian benchmark basins including their location, hydrometric and meteorological record length and nearest climate station. The basic hydrometric measurement at each basin was water discharge or water level using an A-35 Leupold & Stevens recorder. Water quality and sediment measurements were taken periodically at some of the basins. Co-located meteorological instruments were available at only eight basins. The basic meteorological instrumentation package included a Stevenson screen with maximum and minimum thermometers and a thermohygrograh, a Fischer & Porter recording precipitation gauge and a Sacramento storage gauge. Because most of these basins were in remote locations, their service interval ranged from weekly to monthly. A summary of the observation program for the thirteen benchmark basins is given in Table 2. Those basins without co-located meteorological observations had to rely on the nearest climate station for their meteorological data.

PROBLEMS

Although the Canadian benchmark program has been in operation for over twenty years, there has been little use made of the data to date. Only the hydrometric data from the two Maritime benchmark basins, Kelley River and Northeast Pond, have had a comprehensive analysis. This was reported in a study by Pol (1984). There were several reasons for the scarcity of studies using benchmark basin data. These related largely to the nature of the program and its operating constraints.

The long term nature of the program presented difficulties in providing useful results which would have better publicize the program. It was hard to maintain interest after the initial work of establishing the basins was completed and only the mundane tasks of data collection and abstraction remained. Maintaining the funding to operate the program also proved difficult, particularly during the mid 1970s when such programs were not popular and required strong justification for their continuance. Finally, continuity of the program was hampered by staff changes in the operating agencies.

The operating constraints of the program presented problems with data quality and data availability. The "natural state" criterion for the basins generally implied remote locations and long intervals between service visits which affected data quality. The instrumentation available at the time, particularly for the meteorological parameters, resulted in manual abstraction of data from chart records. This problem was accentuated with the increasing constraints on the utilization of personnel within agencies. A further hindrance was that there was only one meteorological observing site established per basin regardless of basin size. This is a limitation with respect to the representativeness of the climatic analysis on the larger basins, but is less of a constraint for the hydrometric data since these are basin integrated values. Finally, there was no central data depository established; thus access to all of the data collected was not a simple procedure. The Catalogue of Meteorological Data from Canadian IHD Research Basin Projects (AES, 1978) was the only effort to at least identify where data were being "archive".

OPPORTUNITIES

There is now renewed interest in long term baseline data sets for the study of global climate change and variability and their impacts. Current or proposed programs such as IGBP, GEWEX, and WCRP provide potential opportunities to promote and rejuvenate the benchmark basin program.

In addition, new sensor technologies combined with the development of reliable and cost effective automatic stations can provide more intensive observation programs and at the same time reduce the requirement for manual abstraction of data. With current communication technology, benchmark sites may be established as part of a network providing real-time data, thus serving a dual purpose.

TABLE 1 Canadian Benchmark Basin Summary

	BASIN	AREA (km²)	HYDROMETRIC DATA	LAT°N LONG°W	METEOROLOGIC DATA	LAT°N LONG°W	NEAREST CLIMATE STATION (km)		LAT°N LONG°W
1.	Tagish Creek, YT	80	09AA011 1965-71	60°18' 134°16'			64	2101300 1942-* (Whitehorse A)^{R}	60°43' 135°04'
2.	Jacobs Creek, B.C.	12	08MH108 1965-80	49°03' 122°33'			2	1104555 1957-86 (Langley Lochiel)	49°03' 122°35'
3.	Mitchell River, B.C.	245	08KH014 1967-82	52°51' 120°45'			57	1090660 1888-* (Barkerville)^{R}	53°04' 121°31'
4.	Brewster Creek, ALTA	109	05BB004 1970-*	51°06' 115°40'	3050824 1970-*	51°08' 115°41'	12	3050520 1887-* (Banff)	51°11' 115°34'
5.	Baker Creek, NWT	126	07SB009 1968-82	62°31' 114°21'	2200495 1969-83	62°31' 114°22'	8	2204100 1942-* (Yellowknife A)^{R}	62°28' 114°27'
6.	Benchmark Creek, ALTA	65	07NB006 1967-84	59°49 111°57'	3075707 1968-83 (Salt River)	59°48' 111°57'	22	2202200 1913-* (Fort Smith A)^{R}	60°01' 111°58'
7.	Ringyouk Creek, NWT	431	06MA002 1969-*	64°16' 96°19'	2302271 1971-74 (Qinguq Creek)	64°15' 96°19'	32	2300500 1946-* (Baker Lake)^{R}	64°01' 96°00'
8.	Pipestone River, ONT	5960	04DA001 1966-*	52°35' 90°12'	601C9PR 1966-* (Karl River)	52°35' 90°11'	124	6016525 1930-* (Pickle Lake)	51°28' 90°12'
9.	Goulais River, ONT	1160	02BF002 1967-*	46°52' 83°58'			59	6057592 1961-* (Sault Ste. Marie A)	46°29' 84°30'
10.	North Magnetawan River, ONT	149	02EA010 1968-*	45°42' 79°19'			42	6113663 1960-* (Huntsville MOE)	45°20' 79°13'
11.	Bassin Temoin Ruisseau St. Louis, QUE	40	02LC043 1968-*	46°22' 74°30			24	7017100 1963-* (St. Donat)	46°19' 74°12'
12.	Kelley River, N.S.	63	01DL001 1969-*	45°35' 64°27'	8202597 1969-84	45°35' 64°32'	8	8294570 1962-* (River Hebert)	45°36' 64°21'
13.	Northeast Pond, NFLD	4	02ZM006 1969-*	47°38' 52°50	8402N73 1970-79	52°50' 52°50'	7	8403506 1942-* (St. John's A)^{R}	47°37' 52°45'

* -- Continuing observations R -- Designated Reference Climate Station

TABLE 2 Canadian Benchmark Basin Observation Program (1988)

Basins

Observations	1	2	3	4	5	6	7	8	9	10	11	12	13
Meteorological Data													
Temperature	-	-	-	C	D	D	D	-	-	-	D	D	D
Humidity	-	-	-	C	D	D	D	-	-	-	D	D	D
Precipitation	-	-	-	C	D	D	D	C	-	-	D	D	D
Wind	-	-	-	-	-	-	-	-	-	-	-	-	D
Sunshine	-	-	-	-	-	-	-	-	-	-	-	-	D
Evaporation	-	-	-	-	-	-	-	-	-	-	-	-	D
Snow Survey	-	-	-	-	-	-	D	-	-	D	-	-	-
Hydrometric Data													
Water Level/ Discharge	D	D	D	C	D	D	C	C	C	C	C	C	C
Sediment	-	-	-	-	-	-	-	-	-	-	-	C	D
Groundwater Data													
Groundwater level	-	-	-	-	-	-	-	-	-	-	-	C	-
Water Quality Data (periodic samples only)	-	D	D	-	-	-	-	-	C	C	-	C	C
Aerial Photograph of Basin	-	D	D	D	-	-	D	D	-	-	-	-	-
	1	2	3	4	5	6	7	8	9	10	11	12	13

Basins

1. Tagish Creek, YT
2. Jacobs Creek, BC
3. Mitchell River, BC
4. Brewster Creek, ALTA
5. Baker Creek, NWT
6. Benchmark Creek, ALTA
7. Kingyouk Creek, NWT
8. Pipestone River, ONT
9. Goulais River, ONT
10. North Magnetawan River, ONT
11. Ruisseau St. Louis, QUE
12. Kelley River, NS
13. Northeast Pond, NFLD

C -- Continuing

D -- Discontinued

Several programs in the planning and implementation stage have similar objectives or useful features relevant to a benchmark basin program. Co-ordination with these could prove mutually beneficial. For example, IWD has installed 350 DCP's at remote stations and AES is planning to co-locate meteorological sensors at 50-75 of these sites. DOE is implementing DCP receive stations at Downsview, Vancouver and Gatineau which will permit real-time data collection and monitoring. Ultimately, quality control and archiving for both hydrometric and meteorological observations from remote sites will also be carried out at these receive stations. It would seem logical to consider existing benchmark basins for automation or alternatively, some of the established DCP sites as new benchmark stations.

The AES is currently in the process of designating climate stations for a Reference network. The long term continuity of these stations will be a priority. Six of the nearest climate stations to the existing 13 benchmark basins have already been designated as reference climate stations. The choice of future benchmark basins should co-ordinate with the climate station network where possible.

Finally, there are possible links with two Unesco programs which focus on northern regions--the IHP Northern Research Basin Program (NRB) and the MAB Northern Science Network (NSN). Canada has been a strong supporter of both international programs. As part of MAB NSN, Canada has proposed the development, monitoring and research in biosphere reserves and other protected areas in northern regions. It would seem logical that the hydrosphere would be a key component in these biosphere reserves and that they may meet the goals of the benchmark basin program.

RECOMMENDATIONS

After reviewing the Canadian benchmark basin program, its problems and current opportunities, the following recommendations are made with regard to the future of the program. The National Research Council, Associate Committee on Hydrology (ACH), with the co-operation of the operating agencies, should review the benchmark basin program and determine its viability in light of current needs for baseline data

* Identify suitable basins from the existing program and establish new basins and observation programs where necessary

* Take the opportunity to co-ordinate with other relevant programs

* Ensure that the resulting benchmark stations be part of the national network, i.e. all resulting data will be put into the national hydrometric and climatological archives

* Publish a regular (bi-annual) summary of the data sets from the program with a water balance for each basin

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Research on Canadian glaciers within the IHD/IHP

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ABSTRACT The paper describes and evaluates glacier research projects included in the Canadian IHD/IHP program. The program of combined heat. Ice and water balance projects conducted within representative basins in the Western Cordillera and the Arctic is described.

The criteria employed for choice of basin and the manner in which research was undertaken are described. An evaluation of the success of the program is made in terms of the development of both Canadian and international understanding of glacier hydrology.

Some projects were specifically designed to accomplish short-term research objectives while others were designed with long-term monitoring and data collection as the basis for understanding the glacier systems. Well-equipped, semi-permanent research facilities were built at several of the long-term monitoring sites; some of these sites have been used also as bases from which to conduct short-term and site-specific research projects.

There has been an evolution in the objectives of some of the long-term projects; especially significant is the evolution from studying small basins very intensively to the incorporation of the knowledge gained into regional scale hydrological models. In future there is likely to be greater emphasis on models which integrate all aspects of high mountain hydrology and models which explore the climate-glacier-hydrology linkages.

RÉSUMÉ Ce rapport renferme la description et l'évaluation des projets de recherche sur les glaciers dans le cadre du programme DHI/PHI canadien; on y décrit également le programme des projets de bilan combinés de chaleur, de glace et d'eau qui sont appliqués dans des bassins représentatifs dans la cordillère de l'Ouest et dans l'Arctique.

Les critères servant au choix du bassin et le mode d'exécution des recherches sont décrits. On présente une évaluation des succès du programme sur le plan de l'accroissement de la compréhension, au Canada et dans la collectivité internationale, de l'hydrologie des glaciers.

Certain projets avaient pour objets précis d'atteindre des objectifs de recherche à court terme tandis que pour d'autres, le contrôle et la collecte de données a long terme constituaient l'élément fondamental pour la connaissance des systèmes des glaciers. Des installations de recherche bien équipées, semi-permanentes, ont été construites à plusieurs sites de contrôle à long terme et certains d'entre eux ont également servi de points de départ pour des projets de recherche à court terme ou portant sur un aspect précis.

Il y a eu évolution des objectifs de certain àlong terme; il convient surtout de noter le passage de l'étude très intensive de petits bassins a l'application des connaissances acquises à des modèles hydrologiques a l'échelle régionale. On verra probablement, à l'avenir, une plus grande insistance sur des modèles qui intègrent tous les aspects de l'hydrologie de

haute montagne et des modèles qui examinent les rapports entre le climat, les glaciers et l'hydrologie.

IHD OBJECTIVES FOR GLACIER STUDIES

In the mid 1960s, under the auspices of Unesco, the IHD program was conceived. The underlying principle was that for a period of ten years hydrologists around the world should collect standardized hydrological and meteorological data within small, carefully chosen research basins. Basins would be selected to encompass the variety of meteorological and hydrological conditions prevalent in each country. Such a data collection system would allow all relevant processes to be studied and the standard data collection format would allow intercomparison of results.

Glacier basins were considered as a sub-set of hydrological basins and, because of the particular nature of the glacier environment, a special set of required measurements had to be devised. Thus the major elements to be studied included the heat, ice and water balances within the basins as well as the interactions between climate and glacier response on short- and long-term scales.

The following topics for glacier research, all of which are relevant to understanding basin hydrology, were specified for special research efforts:

(a) Comparison of mass and energy transfer processes in snow fields and ice in various locations,
(b) Transformation and melting of snow and ice by thermal and mechanical means,
(c) Dynamics of glacier movement,
(d) Development of instrumentation for measuring volume and properties of snow and ice,
(e) Long-term mass balance of glaciers and ice caps,
(f) Erosion and sedimentation caused by glaciers,
(g) Discharge of snow, ice and water through a transverse section through a glacier,
(h) Circulation of water in the interior of a glacier.

Recommendations were also made that, for intercomparisons on an international scale, three chains of research basins be set up - one to circle the globe at about 45°N, another circum-polar chain in the Arctic and a third North - South transect along the western side of the Americas. These recommendations are laid out more fully in Unesco, (1970).

THE CANADIAN IHD REPRESENTATIVE GLACIER BASIN PROGRAM

The government of Canada (initially through the Geographical Branch and subsequently through the Inland Waters Branch, the Water Resources Branch and the National Hydrology Research Institute (NHRI) responded to the international initiative by creating six representative glacier basins - Sentinel, Place, Woolsey, Peyto, Ram River and Decade - at all of which a full set of hydrological, meteorological and glaciological measurements were to be made. These basins were chosen with a number of criteria in mind: they were to be typical, reasonably small, accessible, not heavily crevassed and preferably with some history of previous observation (Østrem, personal communication). The basins were also to be well defined and have single outlet streams which could be accurately gauged.

In addition, a number of research projects at other glaciers were set up and some of these, namely those at Berendon, Per Ardua, White and Baby Glaciers, were subsequently unofficially incorporated into the representative glacier basin program. These have been described by Løken (1970) and by Stanley (1975). The location, characteristics and a brief listing of major standardized data holdings are found in Tables 1, 2 and 3 and Fig.1. For a more complete review of Canadian glacier hydrology and mass balance studies up to the early 1980s reference is made to Young and Ommanney (1984). To put Canadian studies in their world-wide context, reference is made to Collins (1984) and Young (1982, 1985).

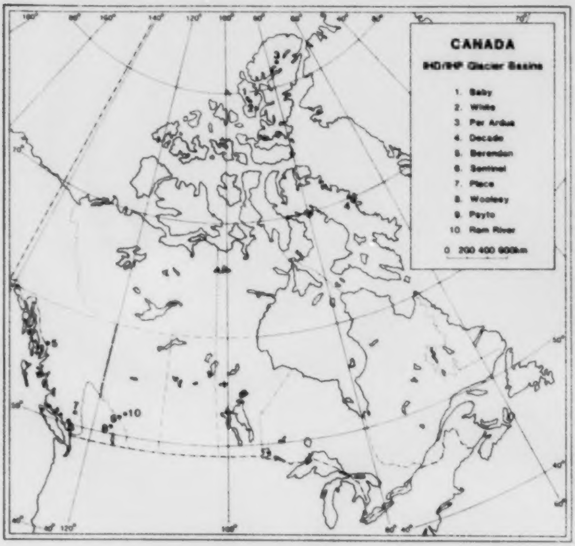
CANADA
IHD/IHP Glacier Basins
1. Baby
2. White
3. Per Ardua
4. Decade
5. Berendon
6. Sentinel
7. Place
8. Woolsey
9. Peyto
10. Ram River
0 200 400 600km
160°
140°
120°
100°
80°
60°
40°
70°
50°
40°
120°
100°
10

FIG.1. Location of Canadian IHD/IHP Glacier Basins.

It is evident from the tables that there was considerable variability in length (and quality) of the data records. Excellent records of basic heat, mass and water balances were obtained from Sentinel, PLace and Peyto Glaciers; heat and mass balance records from White and Baby Glaciers were very good; the records at Ram River and Woolsey were shorter, but still good; records at Berendon, of heat and mass balance, were good for the two years of record (but were sufficient to accomplish the prime goal of the study which was to estimate the likelihood of glacier advance); the records at Decade and Per Ardua were very short and have proven of minimal usefulness for analysis.

TABLE 1 Location of Canadian glacier representative basins.

Glacier Name	Major Region	Specific Location	Latitude	Longitude
Baby	Axel Heiberg Is	Expedition Area	79 26 N	90 58 W*
White	Axel Heiberg Is	Expedition Area	79 27 N	90 40 W*
Per Ardua	Ellesmere Is	Tanquary Fiord	81 31 N	76 27 W*
Decade	Baffin Island	Inugsuin Fiord	69 38 N	69 49 W*
Berendon	Coast Mountains	Steward BC	56 15 N	130 05 W*
Sentinel	Coast Mountains	Garibaldi Park	49 54 N	122 59 W**
Place	Coast Mountains	Birken BC	50 26 N	122 36 W**
Woolsey	Interior Ranges	Columbia Mts	51 07 N	118 03 W*
Peyto	Rocky Mountains	Wapta Icefield	51 40 N	116 15 W*
Ram River	Rocky Mountains	Front Frange	51 51 N	116 11 W*

* Arctic Transect
* N-S Transect in the Americas
* W-E mid latitude transect

TABLE 2 Physical characteristics of glacier representative basins.

Glacier Name	Orient		Elevation (m)			Area	Length
	Ac	Ab	High	Mean	Low	km sq	km
Baby	SW	SW	1175	1000	715	.68	1.60
White	SE	SE	1782	900	53	37.95	15.30
Per Ardua	SW	SW	1705	1150	305	4.26	5.40
Decade	NW	NW	1467	1098	395	8.47	6.10
Berendon	E	E	3210	1350	650	33.40	10.00
Sentinel	N	NW	2100	1800	1525	1.99	2.20
Place	NW	NE	2610	2100	1820	3.96	4.50
Woolsey	NE	NE	2665	2238	1915	3.92	2.90
Peyto	NE	NE	3185	2635	2125	13.40	5.30
Ram River	NE	N	3020	2750	2560	1.80	2.10

In retrospect, the Canadian commitment to the internationally agreed to program was a minimal one. Data were indeed collected at a small number of basins, the most useful results coming from the west-east transect in the southern Cordillera. There was little attempt, however, to promote an integrated approach to data collection and analysis, much less to relate Canadian studies to studies elsewhere. Data summary reports were produced for Sentinel, Place, Peyto and Ram River Glaciers, Mokievsky-Zubok and Stanley (1976a, 1976b), Young and Stanley (1976a, 1976b); reports were not produced for Woolsey and Decade Glaciers. Reports on work accomplished on Axel Heiberg Island are listed in Ommanney (1987). Results of mass balance investigations were, however, reported for all Canadian glaciers through the Permanent Service on the Fluctuation of Glaciers, IASH (1967), IAHS (1973, 1977) and have been summarized by Mokievsky-Zubok *et al.* (1985).

While basic data collection was thus of variable quality, a perhaps unforseen benefit from the program was that at some glaciers, particularly at

Peyto and to a lesser extent at White, many additional special studies were undertaken on a variety of research topics. These studies greatly benefited from the provision of field laboratory facilities provided by the IHD program - indeed they might never have been conducted had not those facilities been available.

TABLE 3 Basic data collections and major agencies involved.

Glacier Name	*Basic data holdings*			*Major Agencies Involved*
	Mass-balance	*Hydrology*	*Meteorology*	
Baby	*1959-86*			*McGill, Trent, ETH Zürich*
White	*1959-86*		*1960-86*	*McGill, Trent, ETH Zürich*
Per Ardua	*1965-73*			*Dept. National Defence*
Decade	*1965-73*	*1965-68*		*NHRI*
Berendon	*1967-69*			*NHRI*
Sentinel	*1965-87*	*1965-87*	*1965-87*	*NHRI*
Place	*1965-87*	*1965-87*	*1965-87*	*NHRI*
Woolsey	*1971-75*			*NHRI*
Peyto	*1966-87*	*1967-83*	*1967-83*	*NHRI, Ottawa, Manchester, Toronto*
Ram River	*1966-75*	*1970-74*		*NHRI*

THE CANADIAN IHP GLACIER BASIN STUDIES

In 1975 the IHD program was renamed the IHP. Many of the existing IHD basin studies continued more or less unchanged in many parts of the world. However, there were some important changes in program emphasis. The most significant of these were a realisation that the research findings obtained in the glacier basins had to be integrated into high mountain hydrology as a whole and that glacier/climate interactions should be more specifically emphasised and studied.

In Canada, studies on six of the ten glacier basins were terminated during or at the end of IHD. On the remaining four, Sentinel, Place, Peyto and White, basic data collection has continued with only little modification into the mid 1980s. The program on the west coast was in fact expanded to include mass balance investigations on several other glaciers. In the Rocky Mountain area, studies on Woolsey and Ram River Glaciers were terminated in 1975 so that more detailed studies could be conducted on the more accessible Peyto Glacier and so that studies of comprehensive high mountain hydrology could be undertaken in the vicinity of Peyto. ETH Zürich continued studies on Axel Heiberg Island, in particular on White Glacier and these studies have been more recently supplemented and continued by groups from Trent University.

It is mainly in the period since the end of IHD that many of the detailed studies on glacier hydrologic processes have been undertaken and written up. Considerable understanding of glacier/climate interactions, internal glacier hydrology and discharge from glacier basins has been gained in this time. In addition useful studies on glacier depth, ice movement and glacier mapping by remote sensing and photogrammetric techniques have been completed. The data collected and the understanding of the processes involved have been and are being incorporated into streamflow simulation models such as the UBC watershed model (Quick & Pipes, 1977).

THE CANADIAN IHD/IHP GLACIER STUDIES IN CONTEXT

It can be argued that for the IHD/IHP in general, and for glacier studies in particular, Canadian hydrological research has been more greatly influenced than have the programs in most other countries. Alpine and Scandinavian countries already had strong glacier programs in existence before IHD and indeed the importance of high-mountain hydrology has been embedded in the national thinking of such countries for a long time. In those regions IHD programs were to a large extent absorbed into already existing national programs. In many less developed nations the IHD programs were never seriously implemented at all and so their effects were negligible. In the mid 1960s and through the 1970s an enormous effort was made by the Federal Government and by many universities to structure their research efforts towards IHD goals, with many good results but sometimes to the detriment of other possible programs.

It is undoubtedly true that a great deal was learned about hydrological processes in a number of small glacier basins. It is also true, however, that the study of total mountain hydrology and regional or large-basin hydrology suffered as a result of so much effort being put into detailed glacier studies. This bias is now somewhat being rectified. Studies to investigate processes in non-glacier covered alpine areas are now being undertaken, and the knowledge of glacier hydrological processes is being incorporated to a greater degree into watershed simulation models.

The whole process of IHD/IHP can now be assessed in a historical perspective. It is apparent that IHD started in a time of economic optimism and expansion. No sooner had the program begun, however, then severe financial restraints were imposed on expenditures. This trend has lasted to the present and seems likely to continue unabated. The failures of the program can largely be attributed to this trend; the more inaccessible and therefore more expensive operations in the Arctic tended to be the first to suffer, and the more expensive of the Cordilleran operations soon followed suit.

Clearly there have been successes and failures in the program. One of the biggest successes was unforeseen at the start of IHD, namely that some of the basins became very successful field laboratories for a variety of experiments and research efforts; this was not only because research facilities existed at glacier sites, but that the wealth of basic data collected proved invaluable in setting the detailed experiments in context.

THE FUTURE

While there have been many basic data reports published and while many papers have been written on a great variety of research topics, there are still many results to be written up from the investigations already undertaken. To a considerable extent there has been an overemphasis on data collection activities without the needed analytical follow-up. Although there have been several studies comparing glacial meteorological and mass balance studies on a world-wide basis, there has yet to be produced a good comparative study of the extensive work carried out on Canadian glacier mass balance, and glacier/climate relations.

In addition there have been no real efforts to evaluate just how "representative" the study basins really are. The very fact that the glaciers chosen had to be of easy access and easy to move around on while neighbouring glaciers are commonly steeper and heavily crevassed begs the question of whether the combination of processes active in the research basins is in fact typical for the region. It can be reasonably argued that the same physical processes are active on all glaciers and thus the results of the studies undertaken can be applied to all glaciers; however, the precise way in which results are to be transposed to glaciers with substantially different surface topographies is still a largely unresolved question. This is a major prerequisite for the application of the results gained in the small glacier basins to larger basins containing dozens or hundreds of glaciers.

The glaciers studies must be integrated into the general context of high-mountain hydrology; this is a necessary pre-requisite to the integration of IHD/IHP results into forecasting models relating to extensive regions. Considerable activity is taking place in this area of research and development. The World Meteorological Organization, over the past several years, has undertaken intercomparisons of runoff models; this exercise has encouraged the integration of rainfall, snowmelt and glacier ice melt into more general models.

While the results of these studies have as yet been little used by water managers (partly because the results have not been adequately integrated into general hydrology and partly because investigation of mountain hydrology is not perceived as a high priority activity) it is likely that the results will be required in future when it becomes apparent that climate change is having a considerable effect on mountain hydrological regimes. The application of some of the latest General Circulation Models assuming doubling of CO_2 in the next 50 - 100 years indicates major changes in the water balance of the Western Cordillera. It may well be that the baseline data collected at small mountain glaciers over the last two decades prove invaluable as the basis for monitoring these predicted climate changes.

CONCLUSIONS

The IHD/IHP has had a tremendous effect on the conduct of Canadian glacier research since the mid 1960s; possibly a greater effect on Canadian research than on the research conducted in any other country.

The whole program would likely not even have been able to start had the economic climate of the 1960s not been so propitious; it is slightly ironic therefore that the failures of the program have been largely attributable to increasingly difficult economic times.

We will never again be in a position similar to that in the 1960s and it is therefore unlikely that we shall see a program oriented towards identical research conducted in a number of small basins.

The final irony is that prior to the IHD a number of studies were being conducted looking at regional hydrology problems; during IHD attention was focused on detailed processes in very restricted areas; the challenge is now seen to be the incorporation of these detailed results into a larger scale picture so that once again we can address problems in regional hydrology.

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Waterford River Basin urban hydrology study - review of the approach

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ABSTRACT The urban areas in the province with increasing population and economic development are experiencing a wide variety of water management problems including flooding, erosion and sedimentation, deteriorated water quality, lowering of groundwater table, loss of recreational facilities and aesthetics. The data on impacts of urbanization on surface water and groundwater in Newfoundland is almost nonexistent, which makes it difficult to develop effective management strategies including urban drainage design criteria. The five year (1980-1985) federal-provincial Waterford River Basin Urban Hydrology Study was designed to examine the processes leading to changes in the hydrologic regime, to apply available models and to recommend solutions to specific water management problems. The study called for a comprehensive approach which included hydrometric surveys, hydrological modelling, groundwater studies, biological surveys, water quality assessment, investigation of flooding, and land use analyses. This paper summarizes the results of various components of the study and outlines the problem and difficulties which were experienced in the hydrometeorological networks design and processing of data, analysis and interpretation of data including the application of hydrologic models, and other aspects of the study. Hydrologic peculiarities of the region such as high rainfall-runoff ratios (80-90%) are highlighted and emphasize the need for developing adequate database in the province. Urbanization did not proceed as anticipated because of economic difficulties and, consequently temporal changes in flow regime in urbanizing watersheds could not be monitored and verified with model results. Despite some unexpected problems, the study has provided valuable results which will help in developing water resource management policies and strategies in urban areas. The approach in general has proved useful and may successfully be adopted in such studies in the future.

RÉSUMÉ Suite à l'accroissement de leur population et au développement économique, les zones urbaines de la province font face à un variété de problèmes de gestion d'eau incluant les inondations, l'érosion et la sédimentation, la détérioration de la qualité de l'eau, l'abaissement de la nappe, la perte de zones récréatives et l'esthétique. Il n'existe que très peu de données sur l'impact de l'urbanisation sur les eaux de surface et souterraines à Terre-Neuve, ce qui rend difficile le développement des stratégies d'aménagement efficaces, incluant des critères de conception de drainage urbain. L'étude fédérale-provinciale d'hydrologie urbaine du bassin de la rivière Waterford, d'une durée de cinq ans (1980-1985), a été conçue pour examiner les processus pouvant modifier le régime hydrologique, pour appliquer les modèles existants, et pour recommander des solutions à des problèmes de gestion de l'eau spécifiques. Le sujet fut abordé de façon globale avec des relevés hydrométriques, de la modélisation hydrologique, des études des eaux souterraines, des relevés biologiques, l'évaluations de la qualité de l'eau, l'étude des inondations, et l'analyse de l'utilisation des terres. Cette communication résume les résultats des différentes composantes de cette étude, et souligne les problèmes rencontrés dans la conception des réseaux hydrométéorologique et le traitement des données, dans l'analyse et l'interprétation des données, incluant l'application de modèles hydrologiques, et dans d'autres aspects de l'étude. Le texte fait ressortir les particularités hydrologiques de la région telles que le fort rapport écoulement/précipitation (80-90%), et souligne le besoin de développer une base de données adéquate pour la province. Le taux d'urbanisation fut plus faible que prévu pour des raisons économiques. Par conséquent, les changements anticipés dans l'écoulement des bassins en état d'urbanisation ne purent être observés et comparés aux prédictions des modèles. Malgré certains problèmes, l'étude a produit des résultats valables qui aideront dans le développement de politiques et de stratégies de gestion de l'eau en zone urbaine. L'approche s'est avérée utile et pourrait être utilisée avec succès dans des études futures.

INTRODUCTION

The problems of urban and urbanizing areas in the Province of Newfoundland such as pollution of sources of water supplies, increasing water demands, flooding and flood damage, loss of recreational facilities and aesthetics, are similar to but perhaps not as serious as those experienced in other parts of the country. The urbanization process in the province has usually proceeded without any analysis of expected long term effects on the hydrologic regime in terms of both water quantity and quality. Land use patterns evolved and urbanization progressed with time. The resulting downstream adverse effects accumulated over a period of time before serious environmental problems emerged. The Waterford River basin is one of the many urbanized areas which not only illustrate the adverse impacts of urbanization but also stress the need for a better understanding of various hydrologic processes and quantitative assessment of the existing and potential impacts of urbanization. In response to growing concerns, the Department of Environment in cooperation with Environment Canada initiated a joint five year study of the basin in 1980 with the following main objectives (Newfoundland Environment, 1978):

(a) To examine the processes leading to changes in the hydrologic regime of the Waterford River basin.
(b) To provide a hierarchy of mathematical models describing hydrologic processes in the watershed.
(c) To recommend solutions to specific water management problems in the basin and to develop guidelines for implementation of similar solutions elsewhere in Newfoundland.

The study has since been completed and its results together with the problems encountered in accomplishing some of the objectives, are summarized in the paper that follows.

STUDY AREA

Physical Features

The Waterford River basin, located near St. John's, has a total area of 77 km^2. Only the upper part of the basin, which measures 53 km^2, formed the study area. Selection of this basin was prompted by its representativeness in terms of urban-related problems; concerns about the magnitude of potential problems as a result of future development with inadequate planning, channel encroachment, and indiscriminate stream alterations; availability of hydrometric data at the outlet of the study area; and projected high rate of development. The remaining part of the basin, downstream of the study area, is fully developed with modified drainage systems, which could have masked the impact of progressing urbanization in the study area.

Geology Soils

The bedrock units consist largely of Precambrian materials, mostly sedimentary in origin with some volcanic deposits. There are major plunging folds and fracture zones in low porosity rocks generally sloping towards the Waterford River and South Brook (King, 1984). About 90% of the study area is covered by a veneer of glacial till (0 - 5m in depth). The soils are coarse-textured and contain stones, gravel and boulders (Batterson, 1984). The internal drainage generally ranges from poor to very poor and this leads to fast hydrologic response during rainfall and snowmelt events.

Hydrometeorology

The climate in the study area is modified by its proximity to the sea resulting in relatively mild winters and cool summers. The average daily maximum and minimum temperatures are 8.6°C and 1.0°C respectively. Precipitation occurs on the average 207 days a year and the average annual precipitation is 1514 mm with fairly uniform distribution. Snowfall accounts for about one third of the total precipitation. High flows usually occur in April due to the combined effects of snowmelt and rainfall. Low flows usually occur during June to August. The minimum and maximum discharges observed during the period 1974-1984 were 0.15 m^3/s and 66.1 m^3/s, respectively.

Land Use and Land Use Changes

The land use types include residential and commercial (17.2%), agriculture (11.7%), forest (34.3%), unproductive land (25%), other lands such as ponds, lakes, rivers, bogs, marshes, channels, etc. (11.8%). Most of the urbanized parts of the basin with a total population of about 30,000, fall under the jurisdiction of the municipalities of Mount Pearl, Paradise and St. John's Metropolitan Board. The study area did not experience any significant change in land use during the period under study as was initially anticipated. There was only a small increase in urban land use (2.1%). The extent of urban areas in any of the sub-basins did not exceed 20-25%.

STUDY COMPONENTS

The complexity of the study required a comprehensive approach covering the effects of urbanization, which included hydrometric surveys, hydrological modelling, groundwater studies, biological surveys, water quality assessments, flooding investigations, and land use and socio-economic analyses. Various component studies are briefly outlined below.

Urban Runoff Study

The main objective of this study was to develop hydrological design principles for urban drainage in Newfoundland. Towards this end, runoff data were collected in a 13 ha test catchment and used to evaluate three runoff computational procedures - the Rational Method, the Illinois Urban Drainage Simulator (ILLUDAS) and the Storm Water Management Model (SWMM) (Marsalek *et al.*, 1985).

Urbanizing Watersheds Study

The objectives of this component of the study were to evaluate the impacts of progressing urbanization on the hydrologic regime; to assess and refine techniques employed in planning, design and operation of storm water management facilities; and to assess the basin response to hypothetical development scenarios.

A network of three hydrometric stations, recording and standard raingauges, snow course and crest gauges provided the data for subsequent analysis and simulation of streamflow by the single event HYMO model and the continuous simulation HSPF model.

Water Quality

The goals of the water quality program were to characterize natural surface water and groundwater quality conditions of the study areas; to assess the influence of cultural activities on physical, chemical, and bacteriological water quality; and to provide data for water quality modelling (Arseneault *et al.*, 1985). Such investigations were conducted at eight sites for surface water and sixteen sites for groundwater quality. The monitoring sites locations permitted the identification of the impacts of various land uses, including urban development, on water quality.

A detailed water quality monitoring program specifying the list of parameters to be studied, sampling frequencies, sampling methodology, preservation techniques was developed and implemented.

Groundwater Study

The objectives of the groundwater component of the study were to identify the major aquifers both in the bedrock and overburden materials; to quantify the groundwater component of the hydrologic system of the basin; and to determine changes in groundwater quality due to urbanization and the processes involved. The investigation plan included construction of 16 observation wells, (bedrock - 8, overburden - 8), establishment of monitoring facilities, collection of water quality samples, monitoring water level changes, and determination of the hydrogeological characteristics of the aquifers. The locations of these wells were based on he existing land uses in the basin (Robinson & Gibb, 1985).

Biological Study

The objectives of this study included the examination of the benthic invertebrate community in relation to water quality and identification of communities which are characteristics of clean and unclean water. Seven sites in 1983 and nine sites in 1984, including one unpolluted control site, were sampled using artificial substrates and indicator communities for water quality identified. These were correlated with the physical and chemical water quality data as indicators of water quality conditions existing at various sites (Stirling & Clemens, 1986).

Flooding Study

This component of the study examined the flooding and erosion problems in the basin, extent of flood prone areas in three selected reaches along the Waterford River, and flood and floodplain management strategies, policies, and guidelines for this basin and other urbanizing areas in the province (Environment Canada and Newfoundland Environment, 1986).

RESULTS

The anticipated urbanization of the study area did not materialize because of unexpected economic difficulties and, consequently, hydrologic changes could not be quantified during the short period of the study. However, the study, first of its kind in the province, provided a valuable data base which will not only help in evaluating such impacts due to urbanization in the future but also assist in the formulation of management policies and strategies at both provincial and municipal levels which will go a long way to minimizing adverse impacts. The study also generated much interest and recognition of the need for a planned approach to the development of urbanizing areas, storm water management, and preservation of water quality. Results of various components of the study in light of overall objectives are briefly presented here.

The urban runoff study involving the application of the Rational Method, ILLUDAS and SWMM produced good results within their operational limits. The procedures and the model parameters recommended in the report will be incorporated in the urban drainage design guidelines in the province. As recommended in the report, further monitoring of this area will be continued for a few more years.

The assessment of the hydrologic characteristics of the Waterford River and changes caused by urbanization was a major task of this study. Because the data collected did not reveal any regime changes, hydrologic models (HYMO and HSPF) were used to predict peak flows for different development scenarios. The doubling of the impervious area would result in increases in peak flow by up to 25% (Ng & Marsalek, 1987). There is no significant increase in flow volume because of the high rainfall-runoff ratios (80-95%). Future studies of both high and low flows using the HSPF model will be based on this existing simulation experience and new data which are being collected by the province. The increase in high flows, resulting from urbanization and predicted by the model, has serious potential for flooding and flood damage which is now increasingly recognized by the municipalities. Stormwater management including storage facilities, adequate design of culverts, bridges, sewer systems, etc., based on new techniques, restrictions on floodplain encroachment, minimum alternation to streams, etc., are becoming an integral part of development policies/practices.

The effects of urban development on physical chemical and bacteriological water quality were very pronounced compared to undeveloped areas. Major ions, dominated by sodium and chloride, had levels higher than typical concentrations in natural waters of the province. High levels of nutrients and trace metals especially during high river discharges were observed. The high bacteria counts observed also indicate the degree of pollution of the surface water caused by urbanization. Considering the fact that water is not used for domestic consumption and that a healthy trout population exists in the river, the surface water quality can be considered to be fair. As a result of this study, action has been taken by the municipalities to correct sanitary and storm sewer cross-connections and regulate construction practices to minimize pollution and enhance water quality. The data collected will help in developing water quality guidelines and objectives by the province.

The groundwater level and quality data collected from the observation wells did not show any effects which could be attributed to various land use activities, including urbanization, with the exception of road salt stockpiling and application. Further monitoring of these sites is continuing on a reduced scale.

The composition of benthic community changed in response to the chemical and physical conditions at the sampling site. Wide ranging differences were found in community diversity, the number of individuals, and the number of taxa. No significant differences in total biomass was detected with the exception of one site. Based on these indices, sites were classified as clean, fair, poor and extremely poor which correlated with the water quality conditions attributed to the effects of urbanization. This technique can satisfactorily be used in other areas to assess water quality.

The flood component of the study accomplished its primary objective of assessing and delineating flood prone areas in the selected reaches based on 1:20 and 1:100 year return periods. Areas affected by erosion, sedimentation, and channel encroachment were identified and documented. The channel sections did not reveal any significant changes due to aggradation and degradation processes. In order to assist in developing floodplain management strategies to minimize flood damage in the future, the Waterford River basin has been included in the Canada-Newfoundland Flood Damage Reduction Program for flood risk mapping of the entire river.

It can be concluded that most of the study objectives were accomplished in varying degrees and useful results were obtained to help in developing appropriate development policies and strategies including regulatory controls.

REVIEW OF THE APPROACH

The successful completion of this comprehensive study is a good example of federal-provincial cooperation and willingness to work together to achieve common goals. The formation of the Technical Committee, sub-committees and Working Groups for various components of the study brought together multidisciplinary teams which benefited from the interaction and opportunities and this in turn broadened the scope and quality and the resultant reports. It also served to mutually transfer technology and information between the federal and provincial personnel.

The Waterford River basin represented a unique opportunity in that it contained all the elements of an urbanizing area - established commercial and residential areas, light industrial parks, developing commercial and residential areas and a potential, (not materialized as anticipated) for ongoing urbanization under the influence of offshore oil development. The multidisciplinary basin study approach was found to be effective in determining and understanding the complex processes producing the observed effects. It is this understanding which makes it possible to predict the changes resulting from managerial decisions on resource management in the same or hydrologically similar basins.

Work plans for various study components were implemented without any major modifications except the biological component of the study which was scaled down to a two year study and confined to benthic invertebrates because of lack of funds. Because of the variability of rainfall observed in the study area, it was felt that an expanded network would have been helpful. Also, it would have been useful to have a hydrometric station on South Brook which is presently undeveloped.

In addition to normal operational problems associated with monitoring facilities and resulting in loss of data, there were other factors which contributed to either loss of data or its reduced quality. Vandalism of crest gauges and the measuring weir used in the urban runoff study was unfortunately common in the initial stages of the study. Some loss of rainfall data was caused by frequent moving of the part-time observers which necessitated the relocation of gauges. The quality of the rainfall data was also influenced by site constraints and reliability of the observers.

Selection of observation well sites and groundwater sampling methodology were considered adequate. After some experimentation it was determined that the most representative groundwater samples were obtained from the deep wells using a Kemmerer tube sampler at the contributing fracture location and from the shallow wells using a peristaltic pump.

Biological sampling using a Surber sampler, as initially proposed, was found not suitable for the objectives of this component of the study because of unfavourable channel bed conditions.

The data collected from the basin proved adequate for the application of hydrologic models, both HYMO and HSPF models. The characteristic hydrologic features of this basin and other basins in the province are reflected in a relatively high rainfall-runoff ratio even in a natural watershed. Limited subsurface storage and the presence of bogs, marshes and other wetlands are some of the contributing factors.

The water quality monitoring program of the basin met all its objectives. The monthly sampling frequency supplemented with event sampling for rainfall greater than 15-20 mm provided an adequate database to assess variability. The CAE sediment sampler provided data on the variability of some selected water quality parameters in relation to flow rates. A full range of parameters could not be sampled because of the inherent plumbing material problem of the sampler. Another area which took away from the interpretation of quality results was the lack of direct analysis of the suspended sediments. The monitoring of bacteriological quality should have been as comprehensive as physical and chemical quality in terms of frequency and site locations. The approach in general has proven to be quite sound. Linkages to the biological community structures and flow regime should have been stronger. Data on quality of precipitation and suspended sediments should have been included to clarify some of the surface water quality results. Water quality modelling could not be attempted because of the time and resource constraints.

CONCLUSIONS

The Waterford River Basin Urban Hydrology Study was, on the whole, a success story. The study was the first of its kind in this province with its unique hydrologic characteristics. The accomplishment of this study is an excellent database including the basic set up of the models which are fully operational and reasonably well calibrated for future studies. The study also helped in the transfer of technology to this province.

The study identified several areas of pollution and their sources which either have been or are being rectified by the City and other municipalities. The results of this study brought out the need for the development of a comprehensive storm water management strategy for this and other basins. Such a study has been initiated by the City. Other municipalities in the region are planning to conduct such studies in their jurisdictions.

The province is formulating legislation to exercise control on storm water management, development in flood plains and other sensitive areas, and wastewater discharges in order to minimize the impacts of urbanization on water resources. The data obtained from this study will also help the provincial government in regulating land use activities which might have impact on water quality or flows. These results can also be sued in other areas of the Province for integrated resource management.

In summary, the basin study and the approach used proved very effective. The study produced an excellent database which will be of immense value to all those concerned with the development of land and water resources in the province.

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Northeast Pond River IHD benchmark research basin in Newfoundland

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ABSTRACT The Northeast Pond River Basin is one of the thirteen benchmark basins established by national IHD committee across Canada to encourage research on hydrological systems in selected geological, geographical, topographical and climatic environments. This benchmark basin is located in the rolling terrain in eastern Newfoundland. The basin area is 3.9 km^2 of which 75% is covered by forest, 17% by bogs and swamps, and rest of the area is covered by ponds and minor vegetation. Apart from its several characteristics that are representative of basins in the region, it is considered a classic basin due to the presence of massive, well-cemented siltstones and sandstones, wherein the difference between precipitation and discharge is readily attributable to evapotranspiration.

During 1969-74 extensive data on climatological and hydrological parameters were collected. However, except for the streamflow, monthly sediment sampling and monthly water sampling activities, all other activities have been discontinued. Provincial as well as Federal agencies have conducted analyses at least on the streamflow data. The results of these analyses are routinely used by governmental agencies in the management of water resources in the province. Studies are planned to examine the effect of acid rain on the water quality in the Northeast Pond River basin. Other studies especially related to rainfall-runoff relationships and water quality assessment are required.

RÉSUMÉ Le bassin de Northeast Pond est un des treize bassins de référence établis par le comité de la DHI à travers le Canada pour encourager la recherche sur les systèmes hydrologiques dans des environnements géographiques, géologiques, topographiques et climatiques donnés. Ce bassin de référence, situé dans la zone ondulée de l'est de Terre-Neuve, comprend 3.9 km^2 dont 75% est couvert de forêts, 17% de tourbières et marécages, et le reste, d'étangs et autres types de végétation. Outre ses caractéristiques qui en font un bassin typique de la région, Northeast Pond est considéré comme un bassin classique: les grès bien cimentés sous-jacents font que les différences entre les précipitations et les débits ne peuvent être attribuables qu'à l'évapotranspiration.

De 1969 à 1974, on procéda à une collecte intensive de données climatologiques et hydrologiques. Cependant, à part la collecte mensuelle de sédiments et d'eau, et des données de débit, toute activité a maintenant cessé. Les organismes provinciaux et fédéraux ont analysé au moins les données de débit. Les résultats de ces analyses sont utilisés couramment par les organismes provinciaux dans la gestion des ressources hydriques de la province. On planifie aussi la mise en place d'études pour examiner l'effet des précipitations acides sur la qualité de l'eau dans le bassin. D'autres études sont nécessaires, principalement sur les relations précipitations-écoulements et sur l'évaluation de la qualité de l'eau.

INTRODUCTION

The nature of hydrologic phenomena and their dependence on the planetary circulation patterns in the atmosphere often requires consideration of very large areas encompassing one or more geo-political boundaries for the optimal design and utilization of regional water resources systems. Based on recognition of the need for broader co-operation, as early as in 1959, a long-term program of international co-operation in scientific hydrology was proposed. Such a program of international co-operation during 1965-74 was coordinated by UNESCO for implementation in Canada and rest of the world as the International Hydrological Decade (IHD). In Canada, the national IHD committee laid emphasis on encouraging hydrological research and consequently, selected projects based on scientific merit, without considering financial and personnel resources. As a result, only 37% of the approved projects were completed and an equal percent of projects were still continuing in 1974 and rest (26%) of the projects were never completed.

One of the several broad objectives of the IHD program was to conduct research on hydrological systems in selected geological, geographical and climatic environments. To meet this specific objective, the national IHD committee initiated a comprehensive hydrological data collection program in thirteen basins [and also identified four more basins as potential candidates for implementation in immediate future (Anonymous, 1970)] distributed across Canada and located in different geological and climatic environments. These basins were termed as benchmark basins because they were selected according to the following criteria (Anonymous, 1970).

1. The basins should be located in certain geographic regions to obtain a broad coverage. Some consideration should be given to the possibility of eventually instrumenting at least two such basins in each broad geographic region in order to lessen the possibility of discontinuity caused by a natural calamity such as a major forest fire.

2. The basins should be located in areas free from any planned or anticipated development. Municipal water supply basins and national parks are most favourable locations meeting such criteria.

3. The basins should be within certain physical size limitations. The limitations stipulated were 2 square miles to 100 square miles (5 km^2 to 260 km^2).

4. If possible, the basins should be relatively topographically homogeneous. For example, entirely below or above the tree line, entirely in a deep soil or shallow overburden or over rock formation.

5. The basins should be relatively accessible to allow for the implementation of a year around monitoring program.

Based on above criteria, in 1969, one such benchmark basin selected in Atlantic provinces was the Northeast Pond River Basin located in Newfoundland. The following presents a summary of research activities carried out in this benchmark basin.

DESCRIPTION OF THE NORTHEAST POND RIVER BASIN

The Northeast Pond River Basin lies between north latitudes 47° 38' and 47° 40', and west longitudes 52° 49' and 52° 51' on the Avalon Peninsula at the southeast tip of Newfoundland, about 12 km northeast of St. John's (Figure 1). The drainage area is 3.9 km² with rolling terrain. Much of the basin is covered with small black spruce. The watershed has several characteristics representative of other basins in the region. For example, 75% of basin area is covered with forest, 17% is in bogs and the remainder is covered equally by ponds and sedges (Fig.1). A summary of pertinent physiographic characteristics for this basin is given in Table 1.

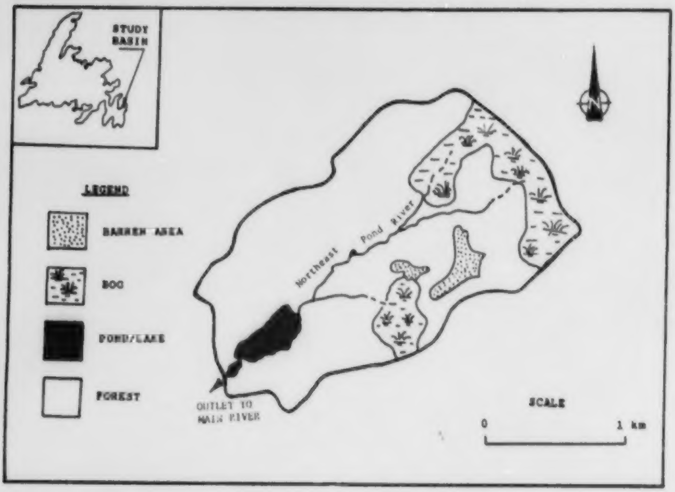
STUDY BASIN
LEGEND
BARREN AREA
BOG
POND/LAKE
FOREST
Northeast Pond River
OUTLET TO MAIN RIVER
N
SCALE
0
1 km

FIG.1 location of Northeast Pond River benchmark basin.

TABLE 1 Physiographic characteristics of the Northeast Pond River basin, Newfoundland.

Drainage area	*3.9 km²*
Lake area	*0.15 km²*
Swamp area	*0.67 km²*
Forest area	*2.94 km²*
Barren area	*0.14 km²*
Length of main channel	*2.63 km*
Slope of main channel	*2.44 %*
Drainage density	*1.04*
Basin shape factor	*1.24*

The basin is covered with fine-grained greenish siltstone and sandstone. In some places the bedrock is covered with thin veneer of stony till. Consequently, the underlying massive well-cemented siltstone and sandstones function as an aquiclude rather than as an aquifer (Anonymous, 1970).

DATA AVAILABILITY

As part of the national benchmark basins program, the data collection activities involved all aspects of hydrological data such as meteorological (precipitation, evaporation, temperature, humidity and wind), hydrometric (streamflow and suspended sediment), groundwater (groundwater levels and groundwater quality), water quality (periodic sampling for such parameters as pH, alkalinity, acidity, suspended solids, nitrogen, phosphorous and various metal) and aerial photographic coverage (at least once in 10 years).

Since its designation as a benchmark basin in 1969, extensive data on various aspects have been collected in the Northeast Pond River Basin during 1969-74. For example, meteorological data on precipitation, wind, evaporation, humidity, temperature and sunshine, continuous records of streamflow, manual sampling of suspended sediment and water temperature, and monthly samples for water quality parameters have been collected. Most of these data are readily available from routine publications of the Water Survey of Canada and the Atmospheric Environment Service.

Because of the presence of unique hydrogeological conditions as mentioned earlier, groundwater monitoring for water levels and groundwater quality was not carried out. No aerial photographic coverage has been completed to date.

Streamflow data is continuous and water quality data is collected monthly. However, meteorological data collection was discontinued in 1974 and suspended sediment sampling was discontinued in 1978.

PAST AND PRESENT RESEARCH ACTIVITIES IN THE BASIN

Peak flow analysis

The Newfoundland Department of Environment and the Environment Canada conducted a comprehensive regional flood frequency analysis for the Island of Newfoundland (Interagency Working Group, 1984). A single station frequency analysis was completed for the Northeast Pond River Benchmark Basin. A log-normal distribution with three parameters (3PLN) was determined to adequately describe the underlying probability distribution of annual maximum instantaneous peak flows at the outlet of the basin. Based on the 3PLN distribution, the peak flows were estimated for the 2, 5, 10, 20, 25, 50 and 100-year return periods as 2.94, 3.94, 4.66, 5.37, 5.69, 6.33 and 7.09 $m^3 s^{-1}$ respectively.

Routine hydrologic data analyses

In 1984, Environment Canada conducted a comprehensive interpretation of the hydrologic data from benchmark river basins located in Atlantic provinces (Pol, 1984). The results of these analyses for the Northeast Pond River Benchmark Basin are summarized as follows.

Consistency analysis Using monthly mass curves of streamflow and precipitation, it was determined that a slight increase in runoff has occurred since 1980. However, a similar increase in precipitation amount was also detected. Since no other changes either caused by data collection activities or resulting from man made activities were noticeable, it was argued that the increase in runoff is caused by corresponding increase in precipitation in the basin.

Statistical analysis The annual maximum (daily and instantaneous) flows, annual daily minimum flows, and annual mean streamflow were separately tested using non-parametric tests as provided in NONPARA computer package (Shiau & Condie, 1980) for independence, trend, homogeneity and randomness. It was determined that each data set can be treated as homogeneous and trend free. However, the results of statistical tests indicated that the data sets can not be treated as independent and consequently also not random.

Flood frequency analysis The flood frequency analysis was conducted on annual maximum instantaneous streamflow using log-normal distribution with three parameters (3PLN). The results of this analysis are identical to that described earlier in the case of regional flood frequency analysis for the Island of Newfoundland (Interagency Working Group, 1984).

Low flow frequency analysis Low flow frequency analysis for various return periods was performed on the assumption that the lowest 1, 3, 7, 14, and 30-day daily minimum streamflow in the basin can be described by the Weibull distribution, Table 2.

TABLE 2 Results of low flow frequency analysis for 20-year return period using LOFLOW computer package (Condie & Cheng, 1982).

Lowest Daily Mean (Day)	*Low Flow Estimate ($m^3 s^{-1}$)*
1	*0.005*
3	*0.005*
7	*0.005*
14	*0.006*
30	*0.008*

Base flow index analysis The base flow index analysis was conducted by defining the base flow index as the ratio of the runoff under the base flow separation line and the total runoff for the same period. Using the BFINDEX computer package (Swan & Condie, 1983), the base flow index was found to be 0.299 with standard deviation of 0.047. The low value of the base flow index for this basin is consistent with other similar small basins (Pol, 1984).

Water balance analysis In the basin area, the values of the mean annual precipitation, mean annual potential evapotranspiration and mean annual runoff are 1560 mm, 520 mm and 1100 mm respectively. A water balance analysis was conducted based on a simplified form of water balance equation (change in storage in a year is equal to the difference in the total yearly precipitation and the total yearly evapotranspiration). Using the average values of runoff and precipitation, and the values of evapotranspiration estimated by the Thornthwaite method, it was determined that the changes in storage accounted for less than 5% of the precipitation.

OTHER RESEARCH ACTIVITIES

To provide a standard reference for surface water quality in the province of Newfoundland, Environment Canada and the Newfoundland Department of Environment (1982), completed a summary report detailing the results of water quality data. This report provides the results of federal and provincial water quality monitoring activities conducted during 1965-1980. The water quality data collected at the Northeast Pond River Basin are summarized in that report. In addition, water quality data from the Northeast Pond River Basin along with other water quality sampling locations in Newfoundland and Labrador was analyzed by Clair *et al.* (1982) to determine sensitivity to acid precipitation. This analysis indicated that most of the province is very sensitive to acid precipitation and that acid sensitive areas on the Island of Newfoundland have generally low pH levels, whereas those in Labrador are high.

The Newfoundland Department of Environment in cooperation with the National Water Research Institute (NWRI) is conducting studies to examine the effect of long range transport of air borne pollutant (LRTAP) on the water quality in the Northeast Pond River Basin. In these studies, emphasis is laid on the seasonal water quality variations in relation to LRTAP and the role of bogs in the release/trap mechanism of pollutant effecting surface water quality.

IMPACTS OF RESEARCH RESULTS ON WATERSHED MANAGEMENT

The benchmark basins provide a good source of data to assess the base information on various hydrologic parameters in strategic locations. These basins because of their locations in different environments are ideal for establishing changes in long range trend of various hydrologic parameters of concern. Although, some hydrologic data interpretation attempts have been carried out on individual benchmark basins, as yet an overall study encompassing all the benchmark basins has to be completed. In absence of such a systematic evaluation of the available information from benchmark basins, it is difficult to assess the overall impact of results from this benchmark basin on our understanding of hydrologic processes. However, it is expected that the results of on-going and planned future studies will provide a basis to identify the long range water management needs in eastern Newfoundland.

Consistently stable regime of suspended sediment load observed in this basin led the IWD to discontinue the sediment sampling activities in the basin. The water yield information obtained from the basin is routinely used by the Newfoundland Department of environment to estimate water yield of basins for rural water supply and other routine activities related to water management. The results of flood and low flow analyses provide basis for various provincial governmental agencies to regulate and manage the water resources and other water related activities.

RECOMMENDATIONS

There is a need to avoid the selection of benchmark/research basins in which a significant lake/pond is located just upstream of the basin outlet as in case of the Northeast Pond River Basin. Such a consideration is important when conducting studies related to water quality and suspended sediment.

Each benchmark basin should be equipped with at least one precipitation station. At present, the nearest precipitation station (St. John's, "A") is located 6.5 km away. A recording type precipitation station should be installed within this basin.

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The Halifax urban watersheds program

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ABSTRACT Five years of research in the Halifax Urban Watersheds are briefly described. The lakes and watersheds being investigated by this program were formerly a portion of the Halifax city water supply. Two of the basins have been retained as emergency water supply for the city of Halifax, while the remainder have been released from protected status and are available for development of various types, ranging from a provincial recreational park to industrial park. The original objectives of the research were related to the determination of the processes which affect water quality and quantity in urbanizing watershed systems. Projects which have been carried out to date include the effects of road salting on water supply lakes; the efficacy of erosion control measures; watershed acidification; and mathematical modelling of lake water chemistry and watershed hydrology. Accomplishments of the program include better communication among resource managers and resource users, and better understanding of techniques for watershed protection. Shortcomings of the program include the length of time needed to reach the original objective and are related both to the lack of human resources and difficulties encountered in defining the hydrology of the system.

RÉSUMÉ On décrit cinq années de recherche dans les "Halifax Urban Watersheds". Les lacs et bassins sous études dans ce programme fournissaient autrefois une partie de l'eau municipale de Halifax. Deux des bassins ont été réservés comme source d'approvisionnement d'urgence, alors que les autre ont été libérés et rendus disponibles pour fins de développement allant de parc récréatif au parc industriel. L'objectif original du programme était la détermination des processus qui affectent la quantité et la qualité de l'écoulement des bassins en voie d'urbanisation. Les projets entrepris à ce jour incluent l'étude de l'influence du salage des routes sur l'eau des lacs, l'efficacité des mesures contre l'érosion, l'acidification des bassins et la modélisation de la chimie de l'eau des lacs et de l'hydrologie du bassin. Les réalisation du programme comprennent une meilleure communication entre les gestionnaires et les utilisateurs des ressources, et une meilleure compréhension des techniques de protection des bassins. Les défauts du programme comprennent le laps de temps nécessaire à l'atteinte de l'objectif initial, et la difficulté de définir l'hydrologie du système.

INTRODUCTION

The Halifax Urban Watersheds Program (HUWP) was established in 1981 as an outgrowth of the interests of the principal investigators regarding urban and agricultural runoff (Waller), and lake eutrophication and biogeochemistry (Hart), and their mutual interest in watershed management in urban and urbanizing areas. There was a perceived need to better understand the physical and chemical processes which determine changes in water quality of surface waters which are affected by development pressures. The goals of the program were (1) to investigate the processes which affect water quality and quantity in urbanizing areas, and (2) to provide a framework in which researchers and managers could examine real problems related to watershed management.

The study watersheds are located near the northwest boundary of the city of Halifax, Nova Scotia. Prior to 1977, when a new water supply system was inaugurated, the watersheds (excluding a single downstream lake) made up a portion of the Halifax water supply system and were protected from development and recreation. The watersheds were chosen as research sites because they represented a variety of basin sizes and potential land uses and because of their location within 5 km of the university campus. Due to the fact that they had been managed by the water utility, they also represented systems for which historical information existed related to limited water chemistry, hydrology, and previous land use.

Original funding for the program was provided by a three year grant from the Natural Sciences and Engineering Council's (NSERC) Research Development Grant Program. Other funding sources include NSERC operating and equipment grants, university support, the Donner Canadian Foundation and research contracts carried out for provincial and municipal agencies.

RESEARCH TOPICS

The five-year research plan developed in 1983 outlined the following broad research goals:

(a) Conduct continuous quantity and quality monitoring of a (then) undeveloped sub-watershed to contribute to understanding of the processes and pollution loads involved in watershed response to urbanization.
(b) Develop special monitoring programs associated with land uses and land use activities expected to occur in the Long Lake watershed.
(c) Perform systematic measurements of the performance of control methods adopted to protect lake water quality.
(d) Perform studies of watershed sources and processes that determine pollution loads in order to improve predictive water quality models.
(e) Conduct comparative studies of water quality in developed and protected watershed-lake systems.
(f) Determine the effects of increased flows on stream morphology and sedimentation.
(g) Examine the effect of acid precipitation on lake water quality.
(h) Determine the long term effects on lake water quality of altered flow regimes and flow patterns.

The research carried out to date has addressed most of these topics with emphasis on hydrologic modelling, effects of development on erosion and reduced water quality, groundwater/lake interactions, the effect of road salting on lake water quality, and the interactions of bulk deposition with vegetation and soils and the consequent effect on surface water quality.

Hydrologic modelling research has centred around the refinement and calibration of the QUALHYMO model, both in terms of hydrodynamics (John, 1985) and water quality (Salah, 1987; Cooper, 1987). Other modelling efforts have been carried out by Pinhey (1984) using OTTHYMO. Preliminary groundwater modelling efforts were also carried out by Attanayake (1986) and Fraser (1986).

Data acquisition needs were determined by Sheppard (1986) and suitable instrumentation designed in conjunction with and fabricated by the Atlantic Microelectronics Institute in Halifax.

Farah (1985) considered potential impacts of altered flow regimes on water quality and quantity during and after development of portions of the study area. The strengths and weaknesses of existing planning processes were examined, as were existing legal and administrative responsibilities of the government with jurisdiction over the watersheds.

The efficacy of methods to control erosion and sediment transport were investigated by MacNeill (1987). The main goal of this research was to document the suitability of various erosion control techniques in use on the water shed during the development of an industrial park and an exhibition site.

The effects of road salting on water supply lakes has been studied for the past five years on the two lakes which make up the emergency water supply for the City of Halifax.

The subject of watershed acidification has been studied for the past two years and preliminary results of this study will be published in two Master's theses during the next year. The first of these deals with changes in stemflow and throughfall chemistry in two representative forest plots. The second body of work will consider the processes affecting soil water chemistry. Additional studies to expand on these two topics and to relate the chemistry of the entire watershed to lake water chemistry are to be initiated during the fall of 1988.

RESEARCH CHALLENGES

During the past six years a number of challenges have been faced by HUWP researchers. These challenges have been primarily related to vandalism, the complexity of the system and the fact that the hydrologic regime and land use within the study area have been subject to a variety of changes.

As with any field data collection effort, potential vandalism has been a concern. To date, the program has not suffered major equipment losses, although the placement of some continuous recording equipment has been less than ideal in order to ensure security.

Difficulties have also arisen regarding the reliability of continuous automatic data collection. In the past these difficulties have been related to the lack of permanent personnel who are knowledgeable about the data acquisition system and the servicing requirements of the various sensors. This problem has been overcome by committing resources to hire a person whose sole responsibility is the maintenance of this system.

The problem of sudden changes in hydrologic regimes and land use have been at times frustrating, although we have attempted to look at such situations as opportunities for further research rather than impediments.

An example of such a problem was the decision to construct an industrial park in the Bayers Lake watershed. A pre-condition of development was the construction of a structure which would allow diversion of drainage from the development site away from the Chain Lakes (the Halifax city emergency water supply) and into Long Lake which is intended primarily for recreation, but which could be used as a supplementary backup supply. While this change required installation of new equipment and revision of some sampling procedures, the opportunity it represented was the reconsideration by water managers of the dogma related to water supply reservoirs. The result has been the establishment of a lake management committee made up of representatives of two provincial government departments, the city government, the Halifax Water Commission, and the Centre for Water Resources Studies. This committee is presently drawing up management guidelines which will maintain water quality in Long Lake at potable levels while allowing recreation and upstream development.

Difficulties associated with the complexity of the system are related to the fact that the two watershed systems have in the past been interconnected and to a limited extent may still be influencing each other due to the existence of a flume connecting two of the lakes. In addition, changes in drainage patterns have been effected during the study period leading to difficulties in interpretation of results. Specific instances are the diversion mentioned above, a pipeline from a lake which was formerly part of the Halifax water supply which has discharged at three different points in the system for varying periods of time over the past seven years. In addition, changes in the operation of this pipeline, the diversion, and the outlet to the largest lake in the system have not always been communicated to the HUWP by the individuals or institutions responsible for their operation.

ACCOMPLISHMENTS

Accomplishments of the program include provision of training in watershed research, a data base containing chemical, hydrometric, and climatological information, increased interaction between researchers and managers, as well as research output in the form of theses and reports.

At a very early stage in the program an intergovernmental liaison committee was established to bring members of a number of federal and provincial departments together on an informal basis to discuss their needs with regard to watershed management and their ability to share in the research effort and results represented by the program. The existence of such a group provided a forum for the discussion of a variety of interests and needs on an informal basis and has proved useful to the committee members in terms of the varied needs of watershed managers.

More specifically, results of research carried out by the HUWP have led to revised methods of transporting, storing, and spreading of road salt at least in the vicinity of the Halifax Urban Watersheds. It has very clearly shown the necessity for improved guidelines and regulations related to erosion and sediment control during and after construction, and has contributed to the revision of guidelines prepared by the Nova Scotia Department of Environment. The management considerations for such use were more easily determined because of the long-term nature of the program and the extensive data base which has been built up during the past seven years. The existence of the program and the level of interagency cooperation have also led to the consideration of multiple use basins as emergency backup water supplies.

AVAILABILITY OF RESULTS

The results of studies carried out by the HUWP are generally available to researchers and managers through reports written at the conclusion of contract research, regular progress reports to contracting agencies, the Centre for Water Resources Studies publication series, or the technical literature. A series of papers on long-term trends in surface water chemistry is presently under preparation for publication during the next year. To a large extent, availability is determined by the "completeness" of the analysis of the data. One PhD and seven Master's theses have been completed during the first six years of the Program's operation and unsummarized data is available to a limited extent to other institutions.

FUTURE RESEARCH

Future research in the HUWP will continue to see a shift from the gathering and interpretation of baseline data to site-specific or task-specific research programs based on short-term alterations of the watershed or specific research topics of interest to the principal investigators. Specific programs include the continuation of the present research on watershed acidification in undisturbed forests, which will be expanded to include effects of acidification in urbanized areas.

The basin approach to research is inherent in the programs carried out by the Halifax Urban Watersheds Program. The Program and the study watersheds have become an integral part of the graduate research program of the university and will continue to be so in the foreseeable future. Although a research watershed might be preferable as a "laboratory", the excitement of carrying out scientific and engineering studies in an ever-changing system carries with it a certain satisfaction, as well as being a constant reminder of the ongoing need for new and better management techniques.

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Watershed studies in Nova Scotia -- successes, failures and future

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ABSTRACT Representative basins were established in Nova Scotia as projects for the International Hydrologic Decade, 1965 to 1974. The title of "Watershed Studies" was assigned to the Sharpe Brook, Fraser Brook and April Brook Basins in Nova Scotia. The Groundwater Division of the Nova Scotia Department of Mines assumed the lead in managing the Basin activities. Research objectives for each basin were "to understand better the relationships of the interconnected parameters of the hydrologic cycle and their effects on the water balance of the basins in a Maritime Climate". A number of studies were completed and publications produced for each basin and the future plan after the IHD period was "to continue monitoring the hydrologic parameters and carry out studies using these data as the need and resources arise." This paper summarizes the research outputs and management. Co-ordinated interest in continuing the watershed studies after 1975 declined leading to fractured data sets and little focused research. Recommendations are offered to begin renewed interest in hydrologic research watersheds in Nova Scotia.

RÉSUMÉ Des bassins représentatifs furent établis en Nouvelle-Écosse comme projets pour la Décennie Hydrologique Internationale (DHI), 1965 à 1974. Le titre "Études de bassins versants" fut assigné aux bassins Sharpe Brook, Fraser Brook et April Brook en Nouvelle-Écosse. La Division des Eaux Phréatiques du Département des Mines de la Nouvelle-Écosse pris charge de la gestion des activités de ces bassins. Les objectifs de recherche de chacun des bassins fut "de mieux comprendre les liens entre les paramètres reliés du cycle hydrologique et leurs effets sur la balance des eaux sous un climat maritime". Un certain nombre d'études furent complétées et publiées pour chaque bassin, et le plan futur suivant la période de DHI fut "de poursuivre la collection des paramètres hydrologiques et d'entreprendre des études a d'lisant ces données comme les besoins et les ressources l'indiquerant." Ce papier présente un sommaire des résultats et de la gestion des recherches. L'intérêt coordonné des diverses agences pour continuer les études des bassins versants suivant 1975 diminua, ce qui amena des ensembles de données fractures et peu de recherche bien visé. Des recommandations sont offertes dans le but de ranimer l'intérêt pour les bassins versants de recherche en Nouvelle-Écosse.

INTRODUCTION

It was stated in the February 1966 "Guidelines for Research Basin Studies" that the overall objective for research basin studies was to "accelerate the study of water resources and the regimen of waters with a view to their rational management in the interest of mankind, to make known the need for hydrological research and education, and to improve our ability to evaluate resources and use them to the best advantage". This objective, restated, that more visible research is needed in support of using and managing water resources, set a challenging goal.

It can be quickly stated that the watershed studies in Nova Scotia accomplished this objective. Details supporting this statement are discussed in this paper. There were on the other hand, difficulties and failures however, "everyone has 20/20 hindsight", therefore, criticisms of weaknesses are offered with a view to the future. It is anticipated that this national symposium, CHS-88, will lead to renewed activity in research basins in Nova Scotia and elsewhere in Canada.

All research basins designated within the IHD program in Canada were categorized into three classifications: representative, experimental, or benchmark. Representative basins were areas set aside to permit study of the existing conditions of a region. Experimental basins were areas in which natural conditions were deliberately modified while benchmark basins were areas set aside to assess long-term trends. In Nova Scotia, four watersheds were designated to be studied during the International Hydrologic Decade of 1965 to 1974 (Fig.1). The Kelley River watershed in northern Nova Scotia was designated as a bench mark basin and continues as such today. The benchmark basin plan was to gather and analyze basic hydrologic data over a long period of time. In a watershed unaffected by human changes the long-term changes or trends should be the result of an equally long-term climatic change.

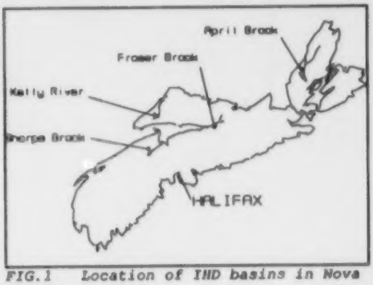

FIG.1 Location of IHD basins in Nova Scotia.

No experimental basins were designated in Nova Scotia, however, the representative classification was assigned to three watersheds. These were Sharpe Brook, Fraser Brook and April Brook. Characteristics of these basins are given in Table 1. The objective of the representative watershed studies was to understand better the relationships of the interconnected parameters of the hydrologic cycle, and their effects on the water balance of the basins in a Maritime climate.

During this review of activities in the research basins, one of the terms of reference developed by the Canadian National Committee for the IHD was found to be worth restating as a critical review standard. This term of reference is:

> "The aim of hydrologic research is not the collection of data, but rather it is an interpretation of these data for use in the solution of management problems...".

This standard should be continuously referenced as the minimum and frequently posed as a question by which success or failure is judged.

PROMPT FOR ORIGINAL RESEARCH

To a large degree the credit for establishment of the original research program and the representative basins goes to Dr. J.P. Nowlan then Deputy Minister, Nova Scotia Department of Mines. Little or nothing was being done in the early 1960's to develop an understanding of the surface water or ground water hydrology of Nova Scotia. The Government of Nova Scotia was committed by Dr. Nowlan to participate in the International Hydrologic Decade. In 1964, the formation of a Groundwater Section within the Department of Mines was started by the initiative of Dr. Nowlan when Mr. J.F. Jones was hired to manage the Groundwater Division. This group was later (1973) transferred to the Department of Environment. One of Mr. Jones' duties shortly after was to implement the section formation and to organize the efforts of well drillers in Nova scotia. Mr. T.W. Hennigar was hired shortly after to implement projects under the IHD program. The foresight of these individuals and the vehicle of the IHD National program came together and are the main reasons for the original research.

At that time, plans were for five watersheds to be selected for the program, however, only three actually proceeded. A benchmark basin in northern Nova scotia, Kelley River, was designated by the Federal participants as a tradeoff for reducing the number of representative basins originally proposed by the Provincial members. The main objective was to investigate components of the water balance in geologically distinct areas of Nova scotia. In particular, the representative basin objective, as previously stated, was to understand better the relationships of the interconnected parameters of the hydrologic cycle and their effects on the water balance of each basin. The various components of the research required input from more agencies than just the Nova Scotia Department of Mines. Excellent co-operation was given by Federal agencies and other Provincial Departments. The original research program lead to several outputs. Some of these are listed later in this paper. Stream gauging was initiated in all basins by the Federal agency, Water Survey of Canada. Messrs. Peters and McBride were instrumental in implementing the stream gauging program.

Intensive monitoring of atmospheric conditions also was concurrently required and implemented by Federal authorities in the Atmospheric Environment Service. Staff involved at that time included Dr. A.D.J. O'Neill, Mr. J. Bruce and Mr. M. McAuley.

THE RESEARCH, PAST AND PRESENT

The reasons for the small research basin approach were need and finances. Water balance data and data for structural design were needed from relatively small drainage areas (less than 10 sq miles) in Nova Scotia. Small drainage areas that could be geologically and geographically quantified were also attractive. In addition, no funding was forthcoming from WMO or UNESCO. Work sharing was the operative method of carrying out the research. Since extra or external resources were not available, operating relatively big research basins was not considered feasible at that time.

A systematic selection method was used to identify the research basins. The basins were selected based on their representativeness of the climate, geology and physiographic uniqueness of western, central and eastern Nova Scotia. This criteria resulted in Sharpe, Fraser and April Brook Basins being selected.

Data collection seemed to be the main thrust or activity of the research. However, the Nova Scotia Department of Lands and Forests produced large scale base maps of topography, land use, and forest type. These maps were also used as the base for surficial and bedrock geology mapping. In addition, papers and reports were produced during the 10 years of formal activity. Authors such as Trescott, Pinder, Hennigar and Jones produced investigations into rainfall/runoff ratios, baseflow chemistry and other aspects. The stream gauging, ground water and atmospheric sensors and recorders were installed early in the program. Following the 10 year formal period of operation most co-ordinated efforts ceased. The research done during the 10 year period constitutes the majority of topics investigated. In addition to the phasing out of co-ordinated data collection, there also appears to have been a phasing out of co-ordinated research using any of the basin data.

In a report dated June 1978, an IWD-AES Analysis Team on the National Basin Program gathered basin data from the Nova Scotian watersheds in preparation for testing in various models. The report concluded that "the climatological and hydrological data routinely collected by AES and IWD for the IHD Program are of adequate quality and reliability for model applications such as those required for most water management purposes". It was also concluded, however, that "it had not been determined whether the quality of data for the majority of the IHD basins are of sufficient high calibre for general use by the scientific community". The report goes on to conclude that "In general the data collected by basin researchers have not been adequately screened and quality checked".

The results of a subsequent data and model test are given in a report by Ambler and Lindeijer, 1978. The SSARR model was applied to the Fraser Brook Basin data set to generate runoff in the basin from 1966 to 1973, inclusive. Overall, the model oversimulated by only 1.4% over the 8 years with the best year having an error of -.2% and the worst year having an error of +8%.

The meteorological data collected at the research basin stations were catalogued by AES in a June 1978 publication. A specific review of data collected at the Kelley River Benchmark station was completed in 1984 by R.A. Pol of Environment Canada. The data sets were tested for independence, trend, homogeneity and randomness in addition to being used to develop flood flow and low flow return periods. A water balance was done resulting in less than 300 mm of rainfall being required to balance the 13 years of data used.

It is assumed that there are other applications of the research basin data and findings, however, they could not all be identified at this time.

STUMBLING BLOCKS AND DIFFICULTIES

All was not perfect during the 10 year active research period. Hennigar recalled that there were 2 main difficulties: "a lack of continuous data and the limited use made of the collected data". Problems developed with volunteer gauge readers, the lack of gauge readers and the lack of funds to hire the perceived staff of readers required. This resulted in a loss of data and/or suspicious periods of data. The second difficulty was perhaps more clearly seen only after the fact. Most project efforts were spent on getting the data rather than developing research projects or doing research. This falls far short of the aim of hydrologic research set by the IHD Canadian National Committee, "an interpretation of these data for use in the solution of management problems." Active promotion of the program also seemed to suffer due to the time needed for managing the data collection program.

The lack of a full time program manager lead to these programs growing with time. Dedication to the research basins amounted to about only 25% of the co-ordinators' time after the first years. Hennigar also noted that only about 50% of his time was focused on the program management during the first year. The other ongoing duties of his position at that time such as responding to requests for assistance in problem solving required as much and, later, more of his time.

COMPLETED STUDIES, SIGNIFICANT FINDINGS AND THEIR IMPACT

The results, impacts, and spinoff from the basin studies, in spite of the difficulties mentioned were substantive. The report "Determination of the groundwater component of peak discharge from the chemistry of total runoff" by Pinder and Jones, 1969, is a widely known reference paper. A summary of publications in addition to the references is given at the end of this paper. The research participants prepared special topic studies in line with their expertise. Studies were completed in all three representative basins. These accomplishments included maps of bedrock, surficial geology and watershed base maps; forest inventories, water quality, sediment and hydrograph analyses. There does not, however, seem to be studies specifically in water balance and the relationships of the interconnected parameters. In addition, during the program, the methodology for ground water advanced. Improved testing and evaluation of well yields, improved mapping of the extent of aquifers and improved pumping tests and aquifer analysis methods were reported as results of impact. The benefits to well drillers have been long lasting in the area of improved water well technology. The coordination of meteorologic and surface water agencies lead to improved understanding of regional rainfall-runoff ratios. A long used rule-of-thumb for regional water yield, 1 cfs/sq mile, was found to be too crude and required adjustment downward.

Overall, the research results improved the general understanding of regional rainfall/runoff relationships. This applied hydrology was picked up by designers, engineers and others dealing with the occurrence of water and the design of hydraulic structures. A better understanding of the surface water and ground water components of total runoff was developed.

The data sets were gathered, processed and archived by various agencies. Meteorologic data were maintained in the AES national system and the surface water data were maintained in the WSC National System. Ground water data were retained in largely unprocessed form by the Province of Nova Scotia. Some consolidated data sets have been setup. These were done by faculty members of the Technical University of Nova Scotia. In addition, the project "IWD-AES Analysis Team on the National Basin Program" (Chin, Environment Canada) the major data sets together.

The last noted accomplishment was a province wide Stormwater Management Committee, formed in the early 1980's. The Committee used the data summaries to develop peak flow and flood flow standards.

RESEARCH BASIN APPROACH OR NOT AND WHAT TO DO DIFFERENTLY

In hindsight, there will always be opinions of what should have been done differently. The opinions offered herein do not suggest that poor results were found, but rather that better results could have been obtained.

The coordinator, T.W. Hennigar, noted that more visibility would have been obtained by setting up demonstration projects and in general by better promotion of the program. Increased visibility and awareness of the opportunities may have increased the use of the data.

Workshops and periodic progress meetings would have also made the basin data more known and used outside of the limited circle of participants.

A coordinator dedicated full time to the program was required to give balanced management to the research. A coordinator with only limited time will address major issues or items needing action at the expense of items such as promotion and long-term follow-up.

There was a definite decline in interest and support for research basins following the end of the Hydrologic Decade. Credit goes to the individuals who continued the momentum in specific basins, however, these were a minority of the original numbers. A renewed commitment is required to revive the integrated basin studies.

In Nova Scotia specifically, and in all other Provinces where interest may have lapsed towards watershed research the following is recommended:

(1) The major players: Nova Scotia Department of Environment, the Nova Scotia Department of Lands and Forests, Inland Waters/Lands, Environment Canada and Atmospheric Environment Service, Environment canada, should meet to discuss renewing an integrated hydrologic research team. Once this team or committee is in place, support and interest should be generated outward to broaden the Committee.

(2) A selection should be made from the former Representative Basins. One of the three may be enough to restart considering today's resource limitations.

(3) A research manager must be appointed separate from the research. Dedicated time is necessary to "move and shake" all aspects of renewed research. In particular, dedicated management time is needed on promotional aspects.

(4) The value contained in the data sets previously made should be studied. A "one-stop-shopping" approach needs to be developed whereby anyone could make a single contact and receive all research basin data. The frustration of having to seek out the data from several sources and in different formats does not aid easy application.

ACKNOWLEDGEMENT

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Nashwaak experimental watershed project

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ABSTRACT The Nashwaak Experimental Watershed Project, located in central New Brunswick, began in 1971. The project was initiated by researchers in the Faculty of Forestry at the University, but expanded into a multi-disciplinary project involving researchers from other university departments and several agencies of the federal and provincial governments. The paper discusses the overall design of the project and its general objectives, focusing mainly on the hydrologic aspects. One small watershed was clear-cut in 1978 and several impacts assessed immediately following the clear-cutting and for several years during the recovery phase.

The wide diversity of participants resulted in valuable collaboration, and provided educational benefits and good public exposure for the project. On the other hand, a lack of clear management responsibility and authority weakened the scientific accomplishments, deprived the project of a sound financial base, and caused some frustrations to the scientists and the management staff alike.

RÉSUMÉ Le projet de bassin expérimental de Nashwaak, localisé dans le centre du Nouveau-Brunswick, a été mis en marche en 1971 par des chercheurs de la Faculté de Foresterie de l'Université du Nouveau-Brunswick. Le projet a vite pris une allure multidisciplinaire avec l'implication de chercheurs de d'autres départements ainsi que de divers ministères des gouvernements provincial et fédéral. Cette communication revoit les objectifs généraux du projet et sa conception initiale, avec emphase sur les aspects hydrologiques. Un petit bassin a été coupé à blanc en 1978, et les impacts du traitement ont été évalués après coupe ainsi que durant plusieurs années de la période de récupération.

Le projet a bénéficié de la diversité des participants au niveau collaboration entre chercheurs, au niveau éducatif et au niveau visibilité publique. D'autre part, le projet a souffert de cette même diversité à cause de l'absence d'un centre de responsabilité et de direction. Cette absence a affaibli les réalisations scientifiques, a privé le projet d'un financement stable, et a généré un certain niveau de frustration chez les chercheurs ainsi que chez les administrateurs du projet.

IN THE BEGINNING . . .

It was 1970 . . . Canada was deeply involved in International Hydrological Decade (IHD) programs . . . and the legacy of Walter Jeffrey was a heightened concern for the forest's influence on the hydrologic cycle. Jeffrey (1970), pointing out the folly of extrapolating the results of watershed research from one hydroclimatic region to another, noted the lack of forest hydrologic research in Canadian climatic regions. Eastern Canadian forested regions with their transitory winter snowpacks were in particular need of hydrologic research. In the Maritimes the only watershed research being conducted was in IHD research basins where experimental manipulation of the land use was not possible. At the University of New Brunswick two new faculty members, Dr. Helmut H. Krause and myself, were anxious to combine our interests in forest soils and forest hydrology in field research on a watershed unit and began searching for a suitable locale. Initially, we investigated the possibility of using a portion of the North Nashwaaksis IHD Research Basin for experimental purposes (specifically, a clear-cut harvest), but considered it unsuitable because of the lack of control over the land use. Eventually we located a site about 25 km northwest of the IHD site, 50 km from Fredericton (Fig.1), where good definition of drainage basins, relatively uniform forest cover, and control over the land use could be assured by the New Brunswick Department of Natural Resources (DNR). The Nashwaak Experimental Watershed Project (NEWP) was born. And we rejoiced.

INTRODUCTION

Universities as institutions are not suitably endowed to handle a comprehensive collaborative program in watershed research. The necessary control of land use and forest operations, and long term investment in hydrologic structures, are usually not available to university researchers. But for the time being the initiative in NEWP rested with UNB Forestry, and principally through Dr. Krause we served as the "lead agency" to arrange with DNR for control of the land use; then we sought and received the participation of Water Survey of Canada (WSC), who installed stream gauging stations, and of the Atmospheric Environment Service (AES), who installed a main climatological station. Research grant support was provided to UNB Forestry researchers from the Canadian Forestry Service (CFS) and AES and the research planning began.

Those of us principally involved at the beginning recognized the value of a much more comprehensive watershed research project. But at UNB - especially within a single Faculty - the range of disciplines necessary for comprehensive research was not available. So we sought the collaboration of other Faculties and other agencies to enable NEWP to be a truly inter-disciplinary, inter-agency project. The Maritimes Forest Research Centre (MFRC) of CFS was approached to become the principal support agency of the project; a meeting of several agencies was held on February 5, 1971 and a committee known as the New Brunswick Inter-Agency Environmental Research Committee was established. The Nashwaak Experimental Watershed Project became its first (and only) project.

Under this newly established structure most of the active coordination of NEWP occurred within a "Scientific Committee," comprised loosely of all the active researchers and collaborators. The chairman of the Scientific Committee (initially Dr. Krause) reported periodically to a Steering Committee composed of senior federal environment and provincial agencies. The scope of NEWP research expanded to include stream biology: algae, benthos and fish; chemistry of precipitation, soil water and stream water; erosion and sedimentation; and forest composition and regeneration; in addition to the climate and water balance components which are the principal focus of this review. These latter components included stream discharge, general climate, basin precipitation, snow cover, and energy balance. Early attention focused on the development of a research plan, generally based on the "paired watershed" concept (Hewlett, 1981), widely used in other watershed projects.

The principal experimental treatment, planned at the onset of the project, was an operational clear-cut harvest; the objectives were expanded to include an assessment of the impacts on the water resource of aerial application of fertilizers and insecticides. Most of this review will relate to the clear-cutting treatment applied to Narrows Mountain Basin. In accordance with

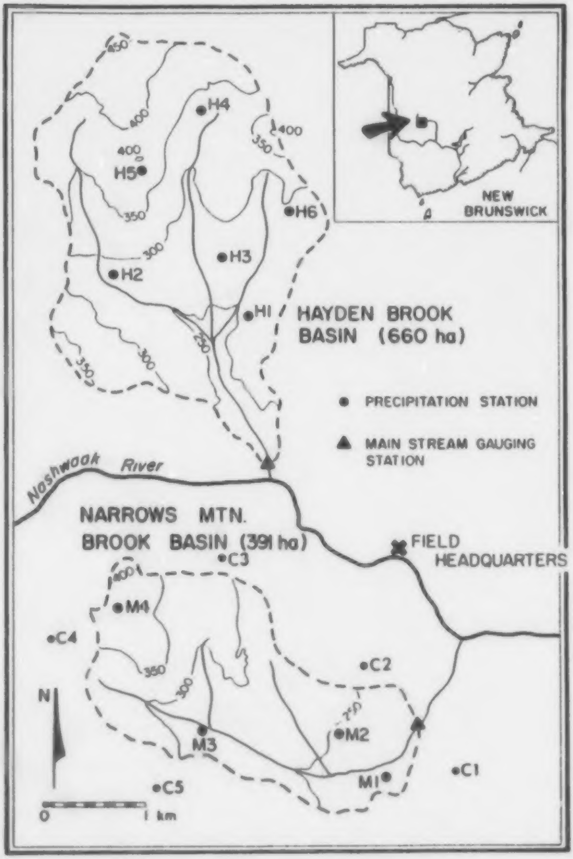

HAYDEN BROOK BASIN (660 ha)
NARROWS MTN. BROOK BASIN (391 ha)
Nashwaak River
FIELD HEADQUARTERS
NEW BRUNSWICK
● PRECIPITATION STATION
▲ MAIN STREAM GAUGING STATION
H1
H2
H3
H4
H5
H6
M1
M2
M3
M4
C1
C2
C3
C4
C5
450
400
350
300
250
N
0
1 km

FIG.1 Map of the Nashwaak Experimental watershed project area showing location of precipitation stations.

the paired-watershed design, a period of calibration was defined, in order to establish relationships between the control basin and the treatment basins. The time periods of the project, in relation to the clear-cutting treatment and the water balance component study, are schematically presented in Fig.2.

A set of objectives was outlined, and later published in a project background document (Anonymous, 1975). The objectives of NEWP are stated in more detail than needs to be repeated here. There is a tendency among scientists to recognize only scientific objectives, and most of our objectives were obviously scientific in nature. But the concept of NEWP also included a demonstration objective and an educational objective. It's important in reviewing the success of NEWP to consider how well we've achieved all of these objectives.

CONTROL OR CHAOS?

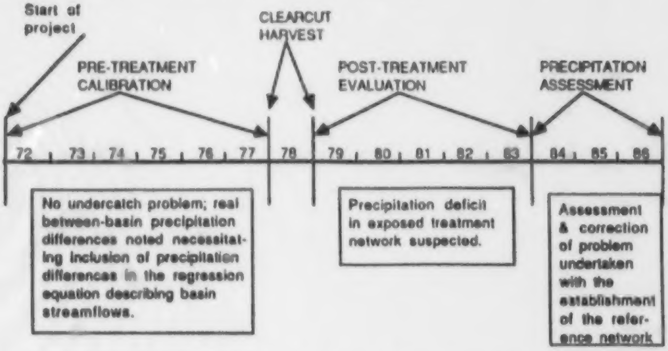
"Control," as applied to NEWP, was a relative term. The compatibility of research and commercial forestry became strained at the beginning. A principal access road was to cross Narrows Mountain Basin near its outlet, and--understandably, because the criteria are similar--the company involved (Valley Forest Products Ltd.) wished to construct the crossing at the site chosen for installation of the stream gauge. The crossing was placed too near the gauging station and on April 30, 1973, during the most extreme runoff event of the project's history, the gauging site was submerged by backwater from the culvert and the streamflow record lost. The gauging station was subsequently moved upstream and a weir constructed.

Another crisis arose in 1974 when a wood supply problem prompted the company to apply to DNR for permission to harvest Narrows Mountain Basin. The calibration period was judged by the researchers to be inadequate for confident assessment of the effect of the treatment. A convincing case was made for deferring the harvest, by detailing the considerable investment of resources and research effort which would be compromised by premature treatment, and the company altered their harvesting plan. This issue, in fact, seemed to make many persons in industry and the non-research government agencies aware of the research value and expected significance of the project. The harvest was not to take place until the researchers agreed in 1978 that the calibration relationships were adequately established.

The harvest operation itself was not without controversy. The company were reminded that a "cosmetic" operation was not the intent, but that "conventional practice" - within government guidelines - was to be followed. During the harvest the placement of a small culvert on one of the temporary extraction roads appeared to be diverting runoff out of the basin. We requested that this be remedied, in spite of the "cosmetic" nature of the remedy, because the diversion would have affected the determination of the water balance. Otherwise, there is no suspicion that the objectives of the project were compromised by the company's harvest operation.

PENNY-WISE?

Many of NEWP's problems rested on the door-steps of us scientists, who were not blessed with adequate foresight. Despite what we considered to be a thorough assessment of the adequacy of streamflow gauging on these small streams, it appears that a decision to accept natural control at the gauging sites was unwise. Eventually, a cement weir did need to be constructed on Narrows Mountain Brook, and the same event which caused the gauging site on that stream to be submerged also disrupted the record on Hayden Brook by


Start of project
CLEARCUT HARVEST
PRE-TREATMENT CALIBRATION
POST-TREATMENT EVALUATION
PRECIPITATION ASSESSMENT
72
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85
86
No undercatch problem; real between-basin precipitation differences noted necessitating inclusion of precipitation differences in the regression equation describing basin streamflows.
Precipitation deficit in exposed treatment network suspected.
Assessment & correction of problem undertaken with the establishment of the reference network

FIG.2. Phases of the Nashwaak Experimental Watershed Project in relation to assessment of basin precipitation (after Palmer, 1988).

rupturing the nitrogen bubbling system and diverting the stream temporarily out of its regular channel. The eminent forest hydrologist, Dr. John Hewlett of the University of Georgia, expressed some dismay about the stability and precision of our measurement capability during a field trip to the site following the 1982 Canadian Hydrology Symposium. Subsequent analysis of the water balance data, however, seems to indicate a reasonable level of confidence. This confidence was accomplished only with considerable effort by WSC to review and occasionally adjust the stage-discharge relationship. The funds required for this unforseen work by WSC might have been better invested in a cement weir at the site in the beginning.

HINDSIGHT: DESIGN REVISITED

Analysis of the water balance data following the clear-cutting treatment revealed an embarrassing fault in the network design for precipitation measurement. Measured precipitation in Narrows Mountain basin was almost constantly below that measured in the control basin, and we soon suspected that the catch efficiency of the standpipe gauges - now unprotected from wind by surrounding forest - was systematically reduced. Belatedly, we realized that a network of precipitation gauges surrounding the basin to be deforested would have provided an unbiased estimate (Dickison et al., 1986). The apparent undercatch was identified as primarily related to snowfall (Blais, 1985), and a special study was undertaken (Palmer, 1988) to derive appropriate adjustments to the winter precipitation measurements in Narrows Mountain basin following clear-cutting. A new network of precipitation stations was established outside the periphery of Narrows Mountain basin (C1-5 in Figure 1), and used as the basis for determining the adjustments.

The fault in the network design seems, like most problems, obvious in retrospect. Yet we took the precaution of subjecting our total project design to review by some well respected watershed research scientists without having the problem recognized. Certainly a more careful review of the issue would have led us to be more wise, because Hewlett had stressed this point in a paper at the FAO symposium in Moscow (Hewlett, 1970).

AND NOW TODAY . . .

NEWP, as designed, has nearly ended. Streamflow measurement continues, together with regular climate monitoring from the headquarters site. But all of the researchers have fulfilled their fieldwork commitments and retired to their offices to undertake new research and/or to contemplate the final reports on their respective NEWP responsibilities. A review of design and conduct of the project are in order if the project itself is to provide an appropriate lesson for those who would undertake similar research in the future.

Scientific achievements

The first assessment of hydrologic effects of clear-cutting was presented at a meeting of the Canadian Society of Civil Engineers shortly after the treatment (Dickison et *al.*, 1981). The "preliminary" estimate of the effect on annual discharge presented at that time was, as noted above, later found to be biased by the change in relative precipitation gauge catch efficiency between the treatment and control basins. Using preliminary results from the study by Palmer (1988), a revised estimate of the first-year effect was provided to Hetherington (1987), which, when compared with the results of other Canadian studies, showed the NEWP results to be comparatively low. Continued review seems to confirm that this later assessment was, strictly speaking, reasonably correct – but misleading. The increases in water yield during the first two years were exceeded substantially in each of the subsequent six years, and we attribute this to the transport and mobilization of snow from the exposed snowpack prior to regrowth of the vegetation. Most of the consequent reduction in water yield would be compensated for by increased yield from outside the watershed perimeter, where the drifted snow would accumulate. Some of the reduction, on the other hand, would be real, due to the higher evaporation of the mobilized snow. By comparing precipitation measurements with snow survey measurements (Daugharty & Dickison, 1982) we have been able to synthesize a recovery rate curve which indicates an increase of 241 mm in the first year following treatment.

The effect of snow transport out of cleared areas has consequences relevant to the interpretation of the results from any watershed study in a region where snow comprises a significant component of the total precipitation. The excess snow which accumulates outside the treated area provides a source of additional runoff during snowmelt, so that a control area which was contiguous to the treatment area would itself be affected by the treatment. This would further reduce the apparent increase in annual discharge caused by the treatment, leading to an erroneous conclusion. In this respect, it is fortunate that lack of suitable access prohibited us from selecting contiguous control and treatment basins in NEWP.

The snow cover component study, perhaps the most extensive of the hydrologic studies, was carried out mainly under the direction of David Daugharty (Daugharty, 1984). Without the detailed information from this study an identification and remedy of the biased water balance assessment could probably not have been made. Nor can this problem be resolved by measuring precipitation with a gauge network outside the basin periphery, because the snow is transported after it has fallen.

Although this review is mainly intended to address quantitative hydrology, a significant study was conducted of the impacts of the treatment on nutrient movement by Krause (1982).

Educational objectives

Research projects are rarely designed with educational objectives in mind. In NEWP it was recognized as an important purpose of the project, and a review of the educational "by-products" is impressive. A total of 6 Masters theses and 22 undergraduate theses, mostly in hydrometeorological topics, have been based on NEWP data. In most instances theses resulted from those persons having worked as student assistants on the project, an educational experience shared by nearly 100 students since the project began in 1971. Even though many of those students were not directly involved in the water resources aspects of the project, it was an exposure through which hydrologic understanding must surely have been gained.

The educational exposure extends beyond the field experience. Classroom exercises in a wide range of disciplines – e.g., soils, hydrology, meteorology, tree biology, stream biology, remote sensing, computer applications – have substantially enriched the instructional programs in forestry and related disciplines, particularly at UNB. It's important, too, to note that these educational benefits do not depend on successful achievement of scientific objectives; one might, in fact, argue that some lessons are more convincingly learned as a result of mistakes! Through talks to schools and public groups, and media articles, this educational benefit has spread well beyond the university and professional communities.

Demonstration objectives

As the most prominent basin hydrology study in the region, NEWP attracted a lot of visitors: hydrologic and forest scientists, biologists, federal and provincial resource managers, politicians, naturalists, university and high school students. NEWP scientists spoke at service clubs, professional societies, public seminars and high schools, provided interviews on TV, radio and in newspapers, and carried out private correspondence with industrial and government resource managers. Regardless of any scientific shortcomings of such a visible project, the image of forest hydrology in the region has been enormously enhanced.

PROJECT MANAGEMENT

I have mixed feelings about the management of a project such as NEWP. The scope required for a truly comprehensive study cannot really be managed by university scientists. Management authority is lacking, and reluctantly assumed even within a department; financial support, usually obtained through research grants, is rarely secure beyond about three years; and university scientists have professorial responsibilities which may pre-empt research management responsibilities at inopportune times. Given the public interest at stake, I am convinced that the management initiative must come from the public service. Admittedly, us university scientists would vigorously resist being "managed" by a federal agency, so the management would have to be undertaken with great skill if not trepidation. In the Maritimes, I believe this management responsibility logically rests with the Canadian Forestry Service; yet CFS-Maritimes has not assumed or been assigned a mandate for significant forest hydrologic research. (One may question, indeed, whether any agency in Canada has assumed an appropriate responsibility for forest hydrologic research.) The CFS scientists involved in NEWP had neither the resources nor the authority to undertake more than their own components of the research. Certainly a provincial jurisdiction the size of New Brunswick could not be expected to exert significant scientific leadership. We who conceived the project are grateful for the efforts of those within CFS and the provincial Natural Resources department who did assume leadership, voluntarily and with inadequate recognition. A sound financial and jurisdictional foundation for NEWP did not exist. It should have. As it was, the commitment to the project faded with the individual scientists.

So what has NEWP accomplished? Its research accomplishments have been more collective than collaborative, and opportunities for something better notwithstanding, those accomplishments have been substantial. Taking into account the total scope of the project's objectives, it has unquestionably advanced the science of forest hydrology in Canada.

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Eaton River representative basin

CLAUDE PESANT
Environment Quebec

ABSTRACT In 1965, the Direction générale des eaus of the Québec ministère des Richesses naturelles started a research and analysis program on the drainage basin of the Eaton River, located in a region where human activity has had little, if and, impact on the hydrological regime. The program started with a complete inventory of climatic and hydrological phenomena (surface and ground water), followed by indepth analysis of these phenomena and, finally, with the hydrological budget of the Eaton River basin. Research projects in hydrology are still in progress in universities and research centres; however, the provincial ministries have gradually pulled out of this area over the last 10 to 15 years. The output of the IHD program remains very useful for studies aimed at better management of our water resources in order to meet present and future needs.

RÉSUMÉ Dans le cadre de la Décennie Hydrologique Internationale (DHI), la Direction générale des eaux du ministère des Richesses naturelles du Québec a entrepris en 1965 un programme d'études et de recherches sur le bassin Eaton dont le régime hydrologique est peu ou pas influencé par l'activité humaine. Ce programme débutait par l'inventaire des phénomènes climatiques et hydrologiques et par la suite des études approfondies de ces phénomènes. Quoique les ministères provinciaux se soient retirés de ce programme, le milieu universitaire poursuit d'autres projets de recherches sur ce bassin. Les acquis du programme sont très utiles pour les études visant à une meilleure gestion de nos ressources hydriques dans le but de conservation de l'environnement.

INTRODUCTION

The International Hydrological Decade (IHD) was created in 1965 by UNESCO in order to:

1. accelerate studies on the hydrological behaviour of hydrographic basins;
2. increase human knowledge of the water cycle; and
3. plan the use of water resources in the most rational way possible.

Within this extensive program, in 1965, the Direction generale des eaux of the Québec ministère des Richesses naturelles started a research and analysis program on the drainage basin of the Eaton River, located in a region where human activity has little, if any, impact on the hydrological cycle. The Eaton river basin is located at the head of the Saint-François river and was instrumented with a very dense measuring network; in addition to being representative of the various conditions of land uses (agriculture, forest and urban expansion) the basin is easily accessible for operation.

The program started with a complete inventory of climatic and hydrological phenomena (surface and ground water), following indepth analysis of these phenomena and, finally, with the hydrological budget of the Eaton river basin. After 1974, the Eaton river project was abandoned because the basin was not selected as part of the IHP that followed the IHD program. This short presentation gives an idea of the research program and of the problems encountered, as well as a perspective of hydrological research in Quebec.

LOCATION OF THE BASIN

The hydrological basin of the Eaton river, a tributary of the Saint-François river, the second largest on the south shore of the Saint Lawrence, is located in the southwestern part of the Province of Quebec. The Eaton river basin is contained between latitudes 45°12' and 45°15' and longitudes 71°15' and 71°42'. The Eaton river joins the Saint-François at East Angus, a community located approximately 27 km upstream of Sherbrooke (Fig.1). Its drainage basin covers 642 km². The relief of the basin is relatively sharp, its altitude varying between 610 metres at the head of the basin and 245 metres at the confluence of the rivers Eaton and Saint-François. The region is in a zone of humid continental climate with cool summers.

MEASURING NETWORKS

As part of the project, the Ministry emphasized the program for sampling the components of the hydrological cycle; 40 stations were in operation during the 10 year period but only 5 stations are now active. Table 1 is a summary of the information on the number of stations in these networks during the International Hydrological Decade (1965-74) and on those still in operation.

TABLE 1 Hydrometeorological measurement network at Rivière Eaton.

Type	*Number active during period*	
	IHD 1965-1974	*1988*
Meteorological stations		
Basic network	7	2
Supplemental network	23	0
Surface water stations		
Basic network	5	1
Ground water (piezometric stations)		
Basic network	5	2

Meteorology

For analysis of its meteorological components, the basin was equipped with two measuring networks: a basic network (seven stations), where several meteorological variables are observed, and an supplemental network (23 stations) where only precipitation data are collected.

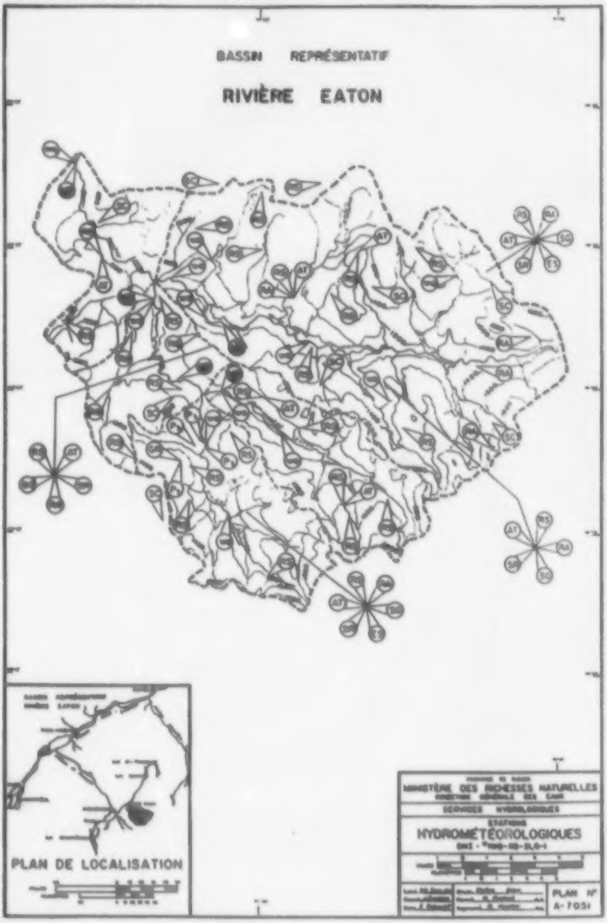
BASSIN REPRÉSENTATIF
RIVIÈRE EATON
AT
SG
ES
SR
RS
RA
SC
PLAN DE LOCALISATION
MINISTÈRE DES RICHESSES NATURELLES
SERVICES HYDROLOGIQUES
STATIONS
HYDROMÉTÉOROLOGIQUES
PLAN N°
A-7051

FIG.1 Location of hydrometeorological measurement stations on the Rivière Eaton.

Surface water

The basin of the Eaton river is equipped with five stations for continuous gauging of the flow of each sub-basin.

Ground water

Five piezometric stations have been set up in the Clifton sub-basin to provide data on the variations of groundwater levels.

ACCOMPLISHMENTS

All data collected are stored into highly suitable banks and are available for computer processing. Fourteen publications have made available the results of the work carried out in that basin.

The study of the representative basin of the Eaton river provided an opportunity to develop research and data utilization methods which can be used on other drainage basins in Quebec and Canada, for example:

- statistical analysis of extremes (high and low flows) with Log Pearson type 3 distribution;
- CEQEAU deterministic hydrological model;
- analysis of hydrographs and their characteristic parameters;
- techniques for calculating flows under ice conditions and with incomplete data, revision of values calculated with more accurate stage-discharge relationships;
- inter-station correlation study (monthly precipitation; daily, monthly flow, etc.).

The data gathered at the Eaton river basin, combined with the physiographic variables obtained from topographic maps, allowed us to:

- define the hydrological characteristics of the flow of the Eaton basin and of its subbasins;
- evaluate the runoff behaviour of a basin from its physiographic, geomorphologic and climatic characteristics; and
- make annual, seasonal and monthly hydrologic budgets.

Although the research program on the representative basin of the Eaton river was dropped after 1974, other research has been conducted in universities:

- At Laval University: application of the modified Ohio model on the Eaton river basin to simulate flows and transferability of the model's parameters to other basins.
- At Ecole Polytechnique: application of hydrological models to forecast Eaton river basin flood flows.
- At the Institut national de recherche scientifique en eau (INRSEAU): using the available data they have improved the development of the CEQUEAU hydrological model, and particularly, the impact on the accuracy of simulated flows by adding information acquired by remote sensing (snow cover) to climatic and snow gauging data; other studies led to adjustment of the model for flow forecasting, application of the coupled quality-quantity model and automatic adjustment of parameters.

The CEQEAU model is an extremely flexible, deterministic matrix model which takes into account the physical characteristics of the basin with their variations in space and time. The division of the basin in a grid allows the best possible description of flow to the outlet of a basin (the vertical flow of water and its progress in the drainage network). Other studies, conducted in collaboration with McGill University, were made on the use of radar to improve the distribution of precipitation in time and space during one event.

In 1971, a rationalization study of the hydrometric network of the Province of Quebec showed an obvious deficiency in the gauging of flows for small drainage basins under 500 km^2. As a result, in 1972 and 1973, the Ministry set up an experimental network of high and low flow gauging stations for 38 basins in the same region as the Eaton river basin. Drainage area of those small basins ranged between 15 and 400 km^2 streamflow data were collected during the open water season of 6 consecutive years; more than 700 summer flood events were analysed and good relations have been developed: Drainage VS Peak flow and Peak flow/Qmax. 24-h ratio; the drainage area is by far the most significant variable related to the peak flow; however due to the deficiency in the precipitation data, the rainfall-runoff relationships were not well defined.

PERSPECTIVES

The projects conducted during the International Hydrological Decade focused mainly on the quantitative aspect of the resource and particularly on the hydrological cycle and its main components. Research projects in hydrology are still in progress in universities and research centres; however in Quebec, the provincial ministries have gradually pulled out of this area in the last 10-15 years.

In the 1960's the resources were readily available and the goals of the hydrological research program timely responded to a need for knowledge in hydrology and water resources management.

Water quality and pollutants are in the news, so, managers of water resources are more concerned with the availability of good quality water, with the evolution of the needs and restrictions imposed on the aquatic environment by industry and agriculture, among other activities. Of course, the drainage basin is still the recognised geographic unit in establishing the quality/quantity budget of the resource and meeting the needs of its population and industry.

The continuation of uses and the conservation of the environment are closely related; in Quebec, they are part of the willingness to protect our environment and, as much as possible, to restore, with the required interventions, those areas which have been disturbed by development. Budget and human resources are channelled towards this goal of environmental preservation, to the benefit of all citizens. Research needs are in the technologies which could remedy the problems of air, water and ground pollution and decontamination. Nevertheless, what have been done in the Eaton River basin is worthwhile and this project was successful; the output of the IHD program remains very useful for studies aiming at better management of our water resources in order to meet present and future needs.

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The Lac Laflamme research watershed: an interim assessment

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ABSTRACT The intention of this paper is to evaluate the research being done at the Lac Laflamme research watershed during the period 1979-1987. The emphasis will not be so much on technical details but on the objectives, accomplishments, difficulties and recommendations to improve the efficiency or productivity of the research. A questionnaire was sent to the 15 principal investigators involved in the research at this basin. It asked information about their research programs, the costs and type of their research (contracts, grants), and their productivity (number of refereed publications, number of MSc. and PhD. diplomas). During these seven years, the government and the universities spent 3.0 million dollars on the research program. If we include the salaries of the 98 scientist-year spent during this time, we can add another 4.9 million which brings the total cost to 7.9 million. Sixty percent of this amount came from universities through grant money. It was difficult to objectively evaluate the research because a standard methodology did not exist. However, if we base our judgement on the number of refereed publications published, we can conclude that as a whole the research was quite efficient since the research teams produced 73 refereed publications. If faced with the same situation, we recommend that first, one manager should be in charge of the watershed; second, more resources should be made available to him to allow a greater integration of the research topics. Finally, three year contracts should be awarded to facilitate the integration of MSc. and PhD. students into the project.

RÉSUMÉ Le but de ce travail est d'évaluer la recherche qui a été effectuée au bassin de recherche du Lac Laflamme durant la période de 1979 à 1987. L'emphase ne se situe pas tellement au niveau des détails techniques mais plutôt sur les objectifs, les accomplissements, les difficultés et les recommandations pour améliorer l'efficacité et la productivité de la recherche. Un questionnaire a été envoyé aux 15 chercheurs responsables de projets de recherche qui est effectuée sur le bassin. Nous leur avons demandé de l'information concernant leur programmes de recherche, les coûts et les organismes les subventionnant ainsi que leur productivité (nombre de publications avec comité de lecture, nombre de diplômes de MSc. et de PhD.). Durant ces sept années, la gouvernement et les universités ont dépensé 3.0 millions de dollars sur ce programme de recherche. Si nous incluons les salaires de 98 scientifique-année dépensés durant cette période, nous pouvons alors ajouter un autre 4.9 millions ce qui monte les coûts totaux à 7.9 millions. Soixante-trois pourcent du 7.9 million provient des universités sous forme de subvention. Il était difficile d'évaluer objectivement la recherche parce qu'aucune méthode standard n'existait; toutefois, si nous basons notre jugement sur le nombre de publications avec comité de lecture, nous pouvons conclure que globalement la recherche était très efficace car les équipes de recherche ont produit 73 publications de ce type. Si nous étions mis en face d'une situation similaire dans le futur, nous recommandons que premièrement, un administrateur devrait être en charge du bassin; deuxièmement, plus de ressources devraient être allouées à cet administrateur pour permettre une plus grande intégration des sujets de recherche. Finalement, des contrats de trois ans devraient être alloués pour faciliter l'intégration d'étudiants à la maîtrise et au doctorat dans les projets.

INTRODUCTION

The purpose of this paper is to review the research being done at the Lac Laflamme research watershed. However, we do not emphasize the scientific point of view i.e. site description right choice of a methodology, sound analysis and discussion but we review it from a manager's point of view. Rather this paper will address the following questions: What prompted the research? What were the main objectives? What research topics and methodologies have been and are currently being tested in the basin? Why was the research basin approach chosen? Why this particular basin? What difficulties have arisen in achieving the objectives? What have been the accomplishments? How do we expect the results to impact the understanding or management of water resources in Canada? Are the research findings being used by researchers and/or water resources managers? If faced with the same research need again, would we select the research basin approach to resolve it?

After first being brought to the public's notice in Scandinavia, acid rain has now become a major concern in North America. Between 1979 and 1985, 36 public opinion studies have been conducted in Canada and the U.S. which included at least one question on acid rain (Neuman, 1986) (Neuman, K., 1986, Water Air and Soil Pollution (31): 1047-1059). Awareness levels of acid rain grew from 30% in 1980 to 94% in 1985 (Neuman, 1986).

In August 1980, Canada and the United States signed a Memorandum of Intent (MOI) on transboundary air pollution to address the rising issue of acid rain. Scientists from both countries met to assess the potential impacts of acid rain on eastern North American resources (Inland Waters/Land, Environment Canada, 1987).

The Long Range Transport of Airborne Pollutants (LRTAP) program was started in 1979 by Environment Canada. One objective of this program was to determine the ability and capacity of the ecosystem of Canada to withstand contamination due to LRTAP and to develop rates of response to changes in atmospheric loading (Elder, F.C., 1982, Long range transport of airborne pollutants: program plan). The Canadian Forestry Service had the mandate to concentrate their efforts on forest soils and forest vegetation, while the Inland Waters were concentrating on inland waters such as lakes and streams. The atmospheric environment service was studying the transport, source and quality of atmospheric deposits. Finally the fisheries and oceans ministry was directing their research toward the impacts of acidic precipitation on the aquatic biota. At the university level, scientists were being contracted by these government agencies to answer specific questions or were doing fundamental research being funded through grants from NSERC (Natural Science and Engineering Research Council), FCAR (Fonds pour la Formation de Chercheurs et l'Aide à la Recherche), WRRSP (Water Resources Research Support Program).

Three different watershed studies were selected to represent three different types of Canadian ecosystems. These watersheds represent a Great Lakes Hardwood Forest (Turkey Lake, Ontario); boreal forest (Lake Laflamme in the Montmorency Forest Experiment Station of Laval University, Quebec); and a marine, bog dominated basin (Kejumkujik National Park, Nova Scotia).

OBJECTIVES OF THE LAKE LAFLAMME WATERSHED STUDY

The objectives were

1) To evaluate the short term and long term effects of atmospheric depositions and concentrations of the various ions on a boreal forest ecosystem (terrestrial and aquatic).

2) To acquire a better knowledge on the basic processes involved in the response of this type of ecosystem to acidic deposition and to quantify pathways and processes from which predictive models can be developed.

To achieve these objectives, two programs were established by Environment Canada of Inland Waters Directorate:

1) the Lake Laflamme ionic budget study;
2) the spring snowmelt study.

In the ionic budget study, chemical loadings reaching the Lake Laflamme watershed in the form of wet or dry deposition (inputs) are measured, computed and compared to the quality and quantity of the ions leaving the aquatic ecosystems (outputs). From the inputs and outputs, a net budget of the chemicals is established and hypothesis are drawn about the long term effects of atmospheric fallout on the chemicals and nutrient cycles within the system.

The spring snowmelt study was created in 1982 following an investigation of a possible spring snowmelt acid shock at Lake Laflamme. Results confirmed that Lake Laflamme was affected by a spring snowmelt acid shock and that over 80% of the annual acidic loading at the outlet of the watershed was recorded during the spring snowmelt period alone. Because of the importance of this episodic event, a program was designed to identify and quantify the processes involved in the response of surface waters during this period. In 1983, progress in the understanding of the processes was such that a project was designed to develop a model to predict the response of surface waters during the spring snowmelt period under different atmospheric loadings for different types of boreal forest ecosystems.

The ionic budget program applies the research basin approach to attain its objectives while the spring snowmelt study program utilizes the integrated research basin approach. The integrated research basin approach is a combination of the following three methods: 1) the research basin approach, 2) the plot approach and 3) the process approach; the integrated approach has to be chosen due to the complexity of the problem. The distinctive feature of the research basin approach is that the dependent variable of concern is the streamflow (quantity and/or quality). The unit land area is normally a watershed. The studies of processes are distinguished by the emphasis on the isolation of variables and normally perhaps, by the intensity and sophistication of measurements. The emphasis is on the revelation of cause and effect relationships as opposed to the accumulation of empirical evidence. The distinctive feature of the plot approach in comparison with studies of processes is that the former is based on a unit area of land surface (homogeneous).

Other research programs have been set up by other agencies and universities (Table 1) to look at other aspects of the problem.

TABLE 1 Topics covered and methodologies used at Lake Laflamme.

Scientist	Collaborators	Methodology	Research programs
CEN. FOR. LAUR.			
Robitaille	Boutin, Phu	Plot, processes	- Determine direct and indirect effects of acid rain on the forest soil.
INLAND WATERS			
Charette-Papineau	-	Bassin	- Determine the ionic budget of the watershed.
FISHERIES AND OCEANS			
Verreault	Walsh, Langlois	Plot	- Determine the survival of brook trout eggs and fries in situ.
INRS-EAU			
Carignan,	Tessier, Villeneuve	Plot, processes	- Biogeochemical model of sulfur dynamics of a boreal ecosystem.
Campbell predictive	Tessier, Verreault	Processes	- Evaluate the chemical desequilibrium degree and develop a model of aluminium speciation in streams.
Jones	Carignan, Hendershot Ouellet, Stein	Processes	- Elucidate the physicochemical role of snow and ice of the annual biogeochemical cycle of nordic ecosystem.
Ouellet	-	Plot	- Study the geochronological and geochemical aspects as well as the composition and number of fossils.
LAVAL-BIOL.			
Moreau, Planas	Lacoursiére	Plot, processes	- Determine the acid rain effects on lotic periphyton and benthos.
LAVAL-SPG			
Fortin	Camiré, Piché	Plot	- Determine the influence of experimental acidification on the soil elements dynamics, mychorrhizae and balsam fir seedlings.
Plamondon	Robitaille, Naud Stein	Plot, processes	- Quantify the microclimate and hydrological cycle components with snowmelt and flowpaths on the basin included.
Stein	Charette, Hendershot Jones	Bassin, processes	- Understand the acid rain impacts on a watershed level through mathematical modelling.
LAVAL-GEO			
Azzaria,	Gélinas	Bassin, plot	- Elucidate the neutralization mecanism of acid rain that falls on the basin and that ends up in the lake. Determine the geologic, mineralogy of the bedrock, deposits and the hydrogeology of the basin.
McGILL			
Hendershot	Jones, Stein	Processes, plot	- Model the chemical interactions between the acid rain and the soil solution.
McMASTER			
Kramer	Rees, Tessier	Plot, processes	- Determine the contribution of lake acidity due to atmospheric deposition using isotopes.
QUEEN'S			
Vanloon	Rutherford, Mern	Plot, processes	- Understand the chemical and pedogenetic effects of simulated acid precipitation on two eastern Canadian forest soils.

TABLE 2 Contracts and grants awarded from 1979 to 1987 at lac Laflamme.

Agency/Principal Investigator (A)	Years of Tenure	Contract		Grants		Total/ Scientist
		Agency	$ x 1000	Agency	$ x 1000	$ x 1000
GOVERNMENT						
LAUR. FOR. CEN. (18)						
Robitaille	1979-1983	LFC	161	-	-	286
	1984-	LFC	125	-	-	
INLAND WATERS (6)						
Charette, Papineau	1979-	IW	56	-	-	56
FISHERIES AND OCEANS (1)						
Verreault	1984-1985	FO	10	-	-	10
UNIVERSITIES						
INRS-EAU (13)						
Campbell	1984-1987	-	-	FO	27	63
	1983-1986	-	-	NSERC (SIC)	36	
Carignan	1987-1990	-	-	FCAR	130	155
	1988-1991	-	-	FCAR (SC)	25	
Jones	1979-	IW	190	-	-	512
	1983-	-	-	NSERC	89	
	1984-1987	-	-	FCAR	76	
	1987-1989	DSS	98	FCAR (SC)	24	
	1983-1987	-	-	WRRSP	35	
Ouellet	1980	IW	10	MEQ	6	16
LAVAL-BIOLOGY (14)						
Moreau, Planas	1982-1988	-	-	NSERC	121	319
	1982-1991			FCAR	177	
	1983-1985			CNSF	21	
LAVAL-FORESTRY (26.5)						
Fortin	1980-1982	CFS	33	-	-	283
	1983-1986	CFS	250	-	-	
Plamondon	1980-1983	CFS	33	-	-	183
	1980-1984	IW	87	NSERC	43	
	1982-1984	-	-	LAVAL	20	
Stein	1983-	IW	96	LAVAL	150	673
	1987-1989	DSS	102	-	-	
	1984-1987	-	-	WRRSP	33	
				NSERC	29	
				NSERC (SSC)	46	
				CFS	122	
	1987-1990			FCAR	75	
				FCAR (SC)	20	
LAVAL-GEOLOGY (7.5)						
Assaria, Gélinas	1980-1983	IW	111	-	-	111
McGILL (0.5)						
Hendershot	1986-1987	IW	10	-	-	62
	1987-1989	DSS	52	-	-	
McMASTER (2) (Kramer)	1984-1986	DSS	25	NSERC	8	33
QUEEN'S (9) (Vanloon)	1981-1984	DSS	220	-	-	220
TOTAL (98)			1,669		1,313	2,982

(A) Year-scientist

Agency abbreviations:

CFS	Canadian Forestry Service, Environment Canada
FCAR	Fonds pour la formation de chercheurs et aide à la recherche
FO	Fisheries and Oceans, Environment Canada
IW	Inland Waters Directorate, Environment Canada
LFC	Laurentide Forestry Center, Envir.Canada (1979-1983), Agriculturre Canada (1984-)
MEQ	Ministère de l'Education du Québec
DSS	Department of Supply and Services
NSERC	Natural Science and Engineering Research Council
SC	Scholarship
WRRSP	Water Resources Research Support Program

Of the 15 principal investigators involved in the research, three university professors; Dr. Carignan, Campbell and Moreau, were recipients of grants from NSERC, FCAR and Fisheries and Oceans only. They choose to work at this watershed due to its proximity to Québec. The facilities at the site, the fact that the watershed was being extensively studied, and the quality of existing data were other reasons. Their task was not part of the two programs established by Environment Canada. This is also true of Dr. Robitaille of the Canadian Forestry Service.

THE LAKE LAFLAMME WATERSHED

The watershed is located in the forest experimental station of Laval University, 80 km north of Quebec City. During the summer of 1979, this first order basin was selected by Environment Canada because:

1. This boreal ecosystem was being protected from the spruce budworm epidemic.
2. Detailed information on vegetation types and surficial deposits was available.
3. Logistic facilities such as room and board, cafeteria, meteorological station, electricity, repairing and storing of ski-doos and other vehicles, already existed at the experimental station.
4. The site was relatively undisturbed and precautions could be taken to prevent human impact on the watershed.

Environment Canada's choice of the integrated research basin approach is well stated by F. Elder in the 1982 Program Plan: "The biogeochemical interactions between acidified precipitation and the various constituents of a basin determine the eventual chemical constitution of streams or lakes of the basin. An understanding of the pathways and interactions throughout the various compartments of the hydrological regime would allow a numerical formulation of the dose/response interactions and permit a quantitative description of levels or degree of reaction to be expected as a result of a scenario of atmospheric loadings. Because these reactions are complex and on the scale of whole watersheds, the calibrated watershed study approach has been adopted. The responses encompass all compartments of the basin ecosystem and therefore require an integrated program to document the effects and responses of all components. These include forest and vegetation effects, soil chemical and biological effects, hydrologic pathway descriptions, water chemistry and biological responses and to a degree limited by the basin scale, wildlife impacts."

DIFFICULTIES

One of the main difficulties of the spring snowmelt study program which appeared early-on as the complexity of the system became apparent, was the definition of the original objectives. In order to attain the objectives in a satisfactory manner, a substantial part of the resources had to be found from outside the federal departmental framework which began the project. The University professors to whom much of the exploratory research was contracted out had to invest an appreciable amount of money from NSERC and other Federal and Provincial granting agencies (Table 2). A further problem was the fact that the university funds were committed for at least a three year period while those of government departments are reviewed and redefined on an annual basis. This resulted in an effort that could not often be sustained and the rate of progress became erratic. If the principle of the experimental study of watersheds is adopted in any future research and monitoring programmes (e.g. IGBP) then some form of long-term funding has to be implemented.

The research programme at Lac Laflamme also suffered from an organisational structure which did not delegate the overall responsibility to one person. Integration between inter-departmental projects were thus carried out on an ad-hoc basis. This was unfortunate because long-term studies should have been undertaken by Fisheries and Oceans department to study the impact on the fish and by the Canadian Forestry Service to study the impact on forest growth.

Apart from the administrative and budgetary difficulties that faced the project, certain technical problems also had to be overcome. There are no standard methodologies, for example, for obtaining data and study of many of the processes such as dry deposition, and meltwater discharge. At least one to two years of development of a methodology is needed to determine whether the hydrological and chemical data obtained is useful for the projected model. This can lead to high costs in field operations as a continual manipulation and supervision of the different methodologies in place is carried out. Until fully automatic systems are available, data collection on a daily basis by technical personnel over fairly long periods can be a serious organisational problem. Finally, and not the least, are the factors that are beyond anybody's control. These can range from lightning strikes which render electronic equipment useless, to falling trees and rodents which contribute to the overall malfunctioning of data-gathering systems.

ACCOMPLISHMENTS

It is hard for the manager to evaluate objectively the research being done at Lac Laflamme because:

1) There is no standard methodology to do so.
2) He does not know all the scientific details of the projects.
3) He may not have the scientific expertise to evaluate those details if they were known to him.
4) He does not have a quantitative figure of what he should expect in relation to the money invested.
5) He does not have much time to devote to this process.
6) The research being done is not finished.

Keeping these difficulties in mind, a cost/benefit approach has been started. All the contracts and grants awarded for each principal investigator from 1979 to 1987 at Lac Laflamme are presented in table 2. It does not include the salaries of the technicians normally hired by the research facilities and who are working on the project.

We calculated that a M.Sc. student contributed 2 scientist-year worth of work while a Ph.D. student was estimated to be 3 years. If we estimate the cost of one scientist-year to be $50000 (including benefits) then the total cost for 98 scientist-year represents 4.9 million dollars of which 3.6 million came from the universities. In reality, a M.Sc. or a Ph.D. student is not hired at that salary, but if we did hire a scientist from a consulting firm at the industry or the University you would have to pay him the salary of a scientist. It therefore represents savings to the agency who contract with the university. Fifty-five scientist-year came from graduate students. The total cost of research is therefore situated at 7.9 million and 63% of this amount was injected by the universities through grant money. The 5.0 million (3.7 + 1.3) does not include any overhead or profit. If this research would have been implemented by consulting firms, it would have cost at least $13 million without profit at an overhead charge of 100% . As for the benefits of the research, we count the number of articles published in refereed scientific journals and proceedings. There are several reasons for this:

1) The work being done is reviewed by independent scientists who have the expertise, which is not necessarily the case for the manager.

2) If the work is published in a refereed journal, it also means that the scientists have added to the body of scientific knowledge and this is important in the long term, if not in the short term.

3) A report is rarely reviewed before it reaches the manager, and if he sends it to scientists for review, he will have to pay.

A manager should also ask about the number of Masters and PhD.'s diplomas resulting from the project. This will give him a quantitative indication of the number of graduates who are well acquainted with the problem and that can be potentially hired for applications of the knowledge found. Another advantage of this numbering scheme is that it is easy to do.

At this point, it is important to add that this method of evaluation is valid only as long as the problem to solve is complex and fundamental research is needed. If the problem is only a technological or applied one, there is not much chance that refereed journal will accept the research. Using the criteria developed above, we also need another basin which we could use to compare our results to see if it had been a success. However, we do not have such a basin. Our accomplishments are summarized in Table 3. The Lac Laflamme program has resulted in the publication of 73 refereed publications. Seventeen students have received their master's degree and seven doctorate students have completed their work on the watershed. Much expertise on the installation and operation of data-gathering systems has been obtained. This will benefit both financially and scientifically any future work which requires the same type of data for hydrogeochemical modelling. The research watershed has also attracted worldwide attention through field visits from participants of international symposia[1] from conferences presented at international conferences, and press conferences. The objectives have been achieved in a satisfactory manner.

IMPACT OF THE RESEARCH

The spring snowmelt study addresses both the hydrology and the quality of surface waters during the spring snowmelt period. The research covers processes and modelling of processes. The research study at Lac Laflamme will lead to a better understanding of the processes involved in the response of surface waters during the spring snowmelt. It will also provide a tool to forecast both the hydrological and chemical responses of surface waters. In doing so it will also be possible to evaluate the possible impact of spring snowmelt water quality changes on the aquatic fauna.

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[1] Acid rain and forest resources conference held on June 17, 1983 at Quebec and sponsored by Environment Canada and the United States Department of Agriculture. Forest resources management - The influence of policy and law held from August 5 to 8, 1984 in Quebec and organised by the International Union of Societies of Foresters, Canadian Institute of Forestry, Society of American Foresters and L'Ordre des Ingénieurs forestiers du Québec.

The ionic budget will provide a better knowledge of the long term variation of water quality in lake ecosystems. It will permit the elucidation of links between the hydrological flux, acidic deposition and lake water quality. The budget should also provide key information on the effect of acidic deposition on boreal forest ecosystems generally.

The research is orientated to answer the needs of resource managers concerned with the problem of acidic deposition. It will answer the following questions: What is the impact of atmospheric depositions on the water quality of boreal forest ecosystems? What is the acceptable level of atmospheric deposition for the boreal forest aquatic ecosystem?

The information will be provided to the Canadian negotiation team charged with reducing atmospheric deposition in Canada and United States.

CONCLUSIONS AND RECOMMENDATIONS

If faced with the same problems, would we do it differently? Yes, we would still select the integrated research basin approach because we believe it provides the best approach to develop such a model. However, we would try to get more out of the money invested by:

1) Having a manager in charge of the watershed who would coordinate the research of the federal departments (inland waters directorate, atmospheric environment service, fisheries and oceans, canadian forestry service) that are supposed to work on the problem.

   This manager would need to be directly involved in the research team and would have some control over the mandate of the agencies involved in the watershed. A certain amount of research money would be allocated to him for distribution to be given to the federal departments or universities to make sure the project is well integrated and sufficient funds are allocated.

2) More resources should be made available to permit the integration of the following aspects to the spring snowmelt study:

   a) determination of the impact of acidic deposition on the forest growth.
   b) determination of the impact of acidic deposition on the aquatic fauna.

   It is also important to channel this money to a "productive" team of scientists.

3) Since it is so much cheaper (3 versus 13 million) to have fundamental research done by universities, 3 year contracts or commitments should be awarded to facilitate the integration of M.Sc. and Ph.D. students into the project.

TABLE 3 Number of publications and degrees originating from the work at Lake Laflamme.

Agency Principal Investigator	*Full papers (refereed)* *Scientific Journal*		*Conference Proceedings*		*Others*	*MSc.*		*PhD.*	
	Pu	*Pr*	*Pu*	*Pr*		*Obt*	*Pr*	*Obt*	*Pr*
LAUR. FOR. CEN.									
Robitaille		*6*	*1*		*1*				
INLAND WATERS									
Charette-Papineau					*10*				
FISHERIES AND OCEANS									
Verreault									
INRS-EAU									
Campbell	*1*	*1*			*1*	*1*			
Carignan	*1*				*1*			*1*	
Jones	*7*	*3*	*2*		*18*	*1*	*1*	*1*	
Ouellet	*3*				*4*				
LAVAL-BIOL									
Moreau, Planas	*11*	*5*	*1*		*10*	*8*	*3*	*1*	
LAVAL-SFG									
Fortin		*1*			*1*				
Plamondon	*4*		*1*		*3*	*4*		*1*	
Stein	*4*	*6*	*2*		*22*	*1*		*2*	
LAVAL-GEOL									
Azzaria		*1*			*5*	*2*		*1*	
McGILL									
Hendershot	*1*				*1*				
McMASTER									
Kramer	*1*					*1*			
QUEEN'S									
Vanloon	*9*							*3*	*1*
TOTAL	*42*	*23*	*7*		*77*	*18*	*4*	*10*	*1*

Obt	*degree obtained*
Pu	*published*
Pr	*in preparation*

Finally, we ought to say that even if this type of research seems expensive we should remember that it is the only way to arrive at a meaningful answer. Crocker and Forster[1] estimated, assuming that the impact of acid deposition is to reduce Canadian forest productivity by 5% per annum then the annual losses to the commercial timber industry is estimated to be $197 million (in 1981 dollars). To this, an annual loss of 1.29 billion (in 1981 dollars) should be added for disruption to recreation and wildlife habitat values. The estimate for the United States in 1978 dollars was U.S. $1.75 billion of which roughly U.S. $600 million was for commercial timber losses. Therefore, if we compare the research costs with the potential economical and environmental impacts of atmospheric deposition we should even invest more.

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The Ruisseau des Eaux-Volees forest experimental watershed, Quebec

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ABSTRACT The Ruisseau des Eaux-Volées experimental watershed was established in 1965 as a part of the IHD. It is located 80 km north of Quebec City in the balsam fir boreal forest at an elevation of 800 m. The temperate cold climate presents a water surplus during each month. The objectives were (1) to establish the relationship between water yield and the climatic, physiographic and biotic factors of the basin, (2) to determine the effects of forestry practices on water yield and stream biology; and (3) to determine ways to apply this knowledge to water and forest management. Streamflow modelling and education are the greatest output of this catchment experiment. Water balance components, low and peak flows and processus on stormflow generation from regional, headwater areas are only available from this watershed. Patch logging 31% of the area had little effect on streamflow and stream ecology. This experiment could not yield the information about the effects of large clear-cutting on water quality and the width of the green strip to be left for stream protection. Lack of continuous funding for the catchment experiment was responsible for most of the elements not fulfilled as part of the objectives.

RÉSUMÉ Le bassin expérimental du Ruisseau des Eaux-Volées a été initié en 1965, comme contribution à la DHI. Il est situé dans la sapinière boréale à 80 km au nord de la ville de Québec et à 800 m d'élévation. Le climat est tempéré froid avec surplus d'eau durant chaque mois. Les objectifs consistaient (1) à établir la relation entre le rendement en eau et les facteurs climatiques, physiographiques et biotiques du bassin, (2) à déterminer les effets des pratiques forestières sur le rendement en eau et l'écologie des cours d'eau, et (3) à determiner comment ces connaissances peuvent être appliquées à l'aménagement de l'eau et de la forêt. La modélisation de l'écoulement et la formation sont les deux plus importantes réalisations reliées au bassin expérimental. Les composantes du bilan hidrique, les débits extrêmes et les processus de génération des crues sur les petites superficies dans cette région sont seulement disponibles à partir de ce bassin. La coupe en assiettes dispersées sur 31% de la superficie a eu peu d'effet sur l'écoulement et l'écologie des ruisseaux. Ce bassin ne permet pas d'évaluer l'effet des grandes coupes sur la qualité de l'eau et la largeur des lisières boisées nécessaires à la protection des ruisseaux. L'absence de support financier continu est responsable de la plupart des éléments non complétés prévus aux objectifs.

INTRODUCTION

The Ruisseau des Eaux-Volées experimental watershed was initiated in 1965 as a joint venture between the Quebec Ministry of Natural Resources and Laval University. It benefited during the first 5 years of some support by the

Federal Government as part of its contribution to the International Hydrological Decade. The aim of this paper is to review the activities related to the experimental watershed, to evaluate to what extent the objectives were fulfilled, and thus derive the needs for the basin approach.

Basin research has been reviewed and criticized by Hore & Ayers (1964), Slivitzky & Hendler (1965), Reynolds & Leyton (1967), Hewlett *et al.*(1969), Hewlett (1970), Ward (1971), and USNC (1977). In spite of its problems and weaknesses, basin studies are useful and necessary for several purposes. Some fundamental hydrologic knowledge has come from studies carried out in basin (Hewlett *et al.*, 1969) which are used as integrators of processes occurring over a land area (USNC, 1977). The basins can form the basis for the extrapolation of hydrological data to ungauged areas (USNC, 1977) and for hydrological forecasting before any treatment is applied (Toebes & Ouryvaev, 1970). It is the ultimate proof of the accuracy of a meteorological water balance and of the functional relationships established through modelling.

It is the only way to obtain practical relations between land uses, evaporative losses, and water yield on an area large enough to satisfy the land manager (Doolittle, 1973; Hewlett, 1970; Hewlett et *al.*, 1969; Hore & Ayers, 1964). Along with water yield, one can consider other environmental concerns such as nutrient cycling (Bormann & Likens, 1969) and effects of fertilization (Gonzalez & Plamondon, 1978).

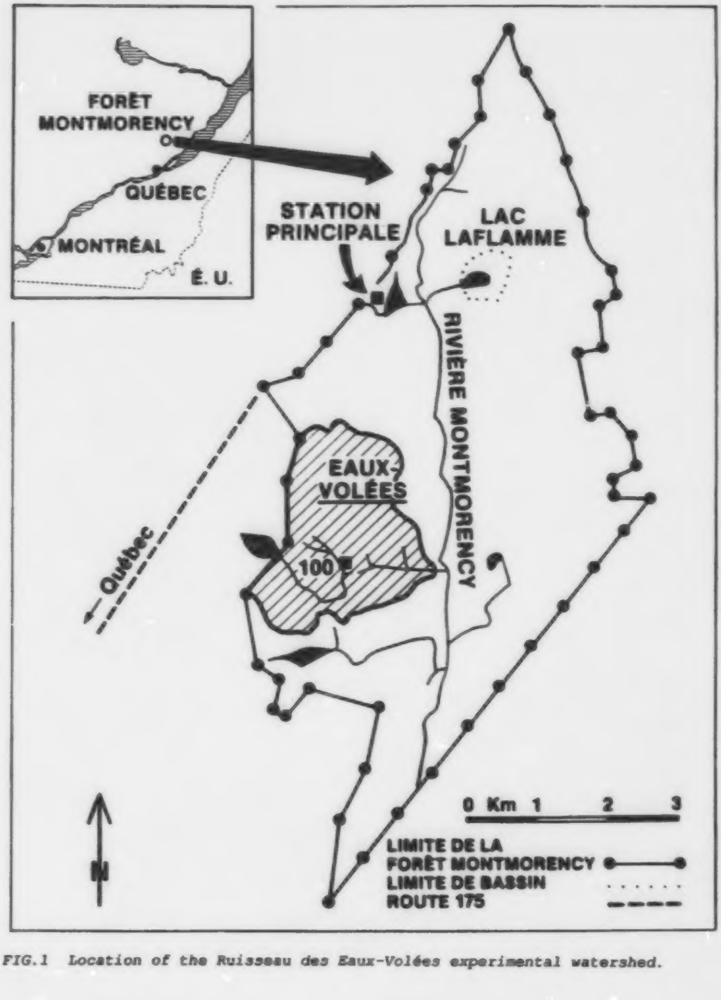
Opposition to watershed studies is based on cost, site selection, size, representativeness, leaks, duration, lack of control, changes due to land use too small for detection, measurement accuracy and analysis of the data. It is also pointed out that the results can be inconclusive because of ignorance of the precise cause and effect relationship. Furthermore, a treatment cannot be repeated under the same conditions. One of the most important points to consider is that the basin experiment is an expensive and time-consuming way to test hypotheses which could be evaluated by other means. Some of these drawbacks can be ruled out in a well-planned experiment. Most of them have been considered as points of caution but not sufficient to abandon basin studies (Hewlett *et al.*, 1969).

LOCATION AND DESCRIPTION

The Ruisseau des Eaux-Volées experimental watershed is located within the Montmorency experimental forest 80 km north of Quebec City at latitude 47° 16′ 20″ N and longitude 71° 09′ 40″ W (Fig.1). It covers an area of 9.17 km^2 and is subdivided into four sub-basins of 1,212, 1.68, 2.33 and 3.94 km^2 respectively (Fig.2). The drainage network is composed of two main streams, the Eaux-Volées and the Aulnaies and a few tributaries. The streambed gradients are gentle except for some places where they are broken by rapids. The altitude ranges between 560 m and 1,000 m. More physiographic features of the basins are reported in Table 1. The average annual precipitation is 1,453 mm. June, July and August account respectively for 121, 168 and 179 mm. According to the Köppen classification, the climate is temperate, cold, and humid with a short and cool summer.

The watershed lies within the Laurentian Uplands of the Canadian Shield which is composed of charnochritic rocks belonging to the Grenville Province. The area is characterized by U-shaped valleys filled with glacial deposits. The depth of the unconsolidated material, mostly composed of basal till, ranges from nothing on the summits to 18 m in the valleys. The most important soil sub-group is the orthic ferro-humic podzol.

Commercial forest, approximately 70% second growth under 50 years of age, covers 95% of the area. The rest is unproductive. It is part of the balsam fir-white birch climax forest composed of 80% balsam fir (*Abies*


FORÊT MONTMORENCY
QUÉBEC
MONTRÉAL
É. U.
STATION PRINCIPALE
LAC LAFLAMME
RIVIÈRE MONTMORENCY
EAUX-VOLÉES
100
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LIMITE DE LA FORÊT MONTMORENCY
LIMITE DE BASSIN
ROUTE 175

FIG.1 Location of the Ruisseau des Eaux-Volées experimental watershed.

balsamea (L.) Mill.), 10% white birch (*Betula papyrifera* Marsh.) and 10% white spruce (*Picea glauca* (Moench.) Voss.) (Plamondon & Naud, 1976).

As a complement to the experimental watershed, especially for extrapolation purpose, two larger rivers were gauged. The Noire and Montmorency river watersheds are located in the same geologic, physiographic, and climax zone as the experimental watershed (Fig.1). The lower drainage density (Table 1) is an artifact caused by the detailed mapping of the water courses on the experimental watershed.

OBJECTIVES AND PERTINENCE

The experimental watershed was set up at the instigation of a hydrologist (M. Slivitzky) and a forester (A. Lafond) who had foreseen the needs for such an installation. Peak flows from small watersheds for culvert dimensioning, hydrologic extrapolations, floods related to logging, hydrologic knowledge applicable to forest management, integration of the well-known soil-stand relations to the broader hydrological cycle and education were among those needs. The watershed experiment was started without a precise written research plan, although the advantages and disadvantages of basin studies were well known (Slivitzky & Hendler, 1964). The basin was located in the Laurentian Uplands because this area feeds many important rivers flowing to the populated Saint-Lawrence river valley, a well defined stream network could be encountered over a small surface, the forest is commercially exploited and a long term control of the land is secured by the statute of the Montmorency Research Forest. This status could offer the continuity needed to carry out long term projects as needed in many aspects of forestry and hydrology.

While the watershed was being instrumented, researchers from different disciplines defined a set of research objectives:

(a) To understand the processes involved in the water cycle and the changes occurring after treatments. It was sought to establish the relationships between water yield and quality, and the meteorological, physiographical, edaphic and biotic factors of the basin;

(b) To determine how and to what extent forestry practices affect water yield, water quality, streamflow behaviour, and stream biology in order to carry out manipulative treatments for desired objectives in water production.

(c) To determine ways to apply this knowledge, for water and land management purpose, such as reducing snowmelt peak flows, curtailing erosion and minimizing water quality deterioration.

The availability of water in Québec exceeds the drinking and industrial needs except in the southwest were summer shortages occur frequently. Some floods are caused by extreme meteorological events or combination of events but most of the high flows are caused by the spring snowmelt with or without rain on wet or frozen soil. Although undisturbed forest watersheds are frequently flood source areas, water quality normally meets drinking standards. The commercial clear-cutting covers an area of 250,000 ha per year (Paillé, 1987). These considerations indicate the validity of studying the effects of man's activities, such as logging, on the land phase of the water cycle, to evaluate the possibility of being able to carry out manipulative treatments for desired objectives in water production, and to establish the relationship between land use and the water cycle for extrapolation purposes.

TABLE 1 Physiographic characteristics of gauged basins at the Montmorency Experimental Forest

	Experimental watershed				Rivers	
Bassin name	Aulnais (7A)	'Aulnais (7)	Eaux-Volées (6)	Eaux-Volées (5)	Noire	Montmorency
Bassin number	51004	51007	51002	51003	51006	51005
Streamflow''	66/12	71/11	65/10	67/01	66/09	66/09
Area (km^2)	1.22	2.33	3.94	9.17	58.8	269.4
Mean Elevation (m)	875	806	823	810	891	847
Land Slope (%)	14.4	20.3	7.7	7.6	20.8	18.1
Drainage Density	2.16	1.85	1.71	2.42	0.77	1.09
Channel Slope (%)	9.7	3.0	2.3	2.2	1.36	0.75
Length (m)	1036	2940	2499	5090	17396	41395
Tortuosity	1.05	1.04	1.01	1.18	1.04	1.03
Area Lake (%)	0	0.15	0.03	0.04	1.7	3.0
Area Swamp (%)	0	1.9	0	0.46	0	0
Area Forest (%)	100	98.0	99.97	99.5	98.3	97.0

' Excluding 7A (Fig.2)

'' First measurement (year/month)

EVALUATION OF THE RESEARCH PROGRAM

Basic hydrometeorological information

Streamflow The sub-basin arrangement (Fig.2) is a combination of the paired (7A, 6) and the nested pair basin design (Hewlett & Pienaar, 1973). Stations 5, 6 and 7A are equipped with V-notch weirs whereas concrete bags are used for watershed 7. Noire and Montmorency Rivers were gauged in natural sections until August 1982. The flow was recorded every 15 minutes with pressure gas bubbling system. Accuracy was affected occasionally by severe freezing, spring ice flow, and in one case by sediment accumulation.

Meteorology The meteorological network includes a permanent and fully instrumented station 10 km away from the centre of the watershed. Temperature and humidity are recorded at three points with hygrothermographs. Nipher shield gauges (2) are utilized to measure daily snowfall. During the first fifteen years it was completed by sixteen precipitation stations equipped with standard rain gauges (2), weekly totalizer gauges (15), or recording gauges (4) and one station under the canopy was equipped with a thermograph and two black disc atmometers.

The meteorological network on Ruisseau des Eaux-Volées experimental watershed was based on three criteria: the instrumentation available from governments, the time needed for observations and that the agencies agreed to support one full-time observer.

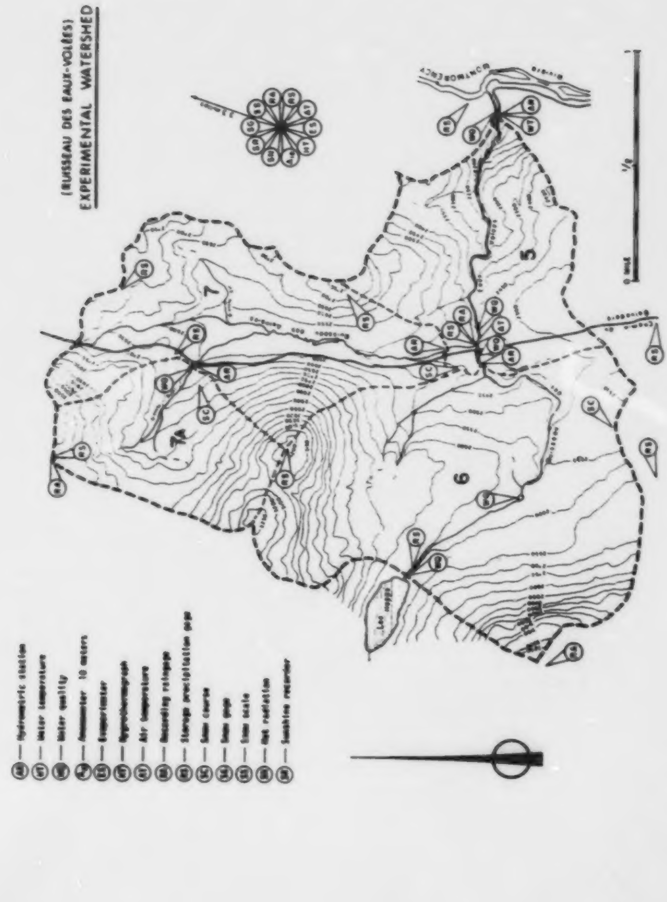
Watershed based research

Streamflow generation A network of monitoring wells adjacent to the stream was used to test the water ridging hypothesis (Sklash & Farvolden, 1979) which is a physical mechanism explaining the important contribution of groundwater to stormflow as measured by environmental isotope tracer techniques. Field and simulated results at Ruisseau des Eaux-Volées support the validity of the groundwater ridging hypothesis (Sklash & Wilson, 1982).

Fertilization About two thirds of Watershed 7A was fertilized in June and the rest in September 1973 with 155 kg/ha of nitrogen. The concentrations of urea, ammonium-nitrogen, and nitrate-nitrogen increased significantly during the application period and the week following it, but the concentrations never went above drinking standards. From the streamflow measurements it was possible to evaluate the total nitrogen losses. Fertilization had no measurable effects on pH, turbidity, colour and on dissolved oxygen, calcium, magnesium and iron concentrations (Gonzalez & Plamondon, 1978).

Water balance and interception The watershed experiment defined the annual water balance of the area and the importance of interception was evaluated from plot studies (Fréchette, 1969; Plamondon *et al.*, 1984a). The interception loss, accounting for 40 to 50% of the annual evapotranspiration, indicates the potential effects of cutting on the water balance. However, it was demonstrated that the logging debris and shrubs had a similar interception four years after cutting (Prévost & Plamondon, 1987).

Effects of patch clear-cutting on streamflow Patch logging 31% of watershed 6 had no significant effect on annual, seasonal and monthly flow. It did not change either the shortest number of consecutive days that produce 10, 25 and 50 percent of this flow (Plamondon & Ouellet, 1980). Spring runoff


(RUISSEAU DES EAUX-VOLÉES)
EXPERIMENTAL WATERSHED
Hydrometric station
Water temperature
Water quality
Anemometer 10 meters
Evaporimeter
Hygrothermograph
Air temperature
Recording raingage
Storage precipitation gage
Snow course
Snow gage
Snow scale
Net radiation
Sunshine recorder
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7A
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FIG.2 Location of instrumentation on the Ruisseau des Eaux-Volées experimental watershed.

was not significantly affected except in 1977 where the total outflow between the time of rising stream flow and the peak was increased. These results differ markedly from those obtained in eastern U.S. after clearing one third of the land area (Hornbeck & Federer, 1975; Douglass & Swank, 1972). However, they are similar to the results obtained by Fowler *et al.* (1987) after patch-cutting 17 and 40% of two watersheds covered with coniferous forest in northeastern Oregon.

Effects of patch clear-cutting on stream ecology The increased concentration of suspended sediments during rainstorms seems to have affected the primary productivity, the drift of invertebrate benthic fauna and the relative abundance of insects. The conductivity and the concentrations of iron and phosphate were increased. Dissolved oxygen and pH diminished whereas the nitrate remained constant. It can only be concluded that no drastic change in stream ecology occurred (Charlois, 1977; Elouard, 1977).

Complementary plot studies

Radiation and evapotranspiration After clear-cutting, the net radiation was reduced to 89% of the value above the forest mainly because the albedo increases from 7 to 18% (McCaughey, 1978a). The energy balance approach was used to estimate the evapotranspiration above the forest (McCaughey, 1978b). The coefficient in the Priestly-Taylor equation range from 0.67 when the volumetric soil moisture content of the top 10 cm is 22% to the equilibrium value of 1.26 at 32% soil water content.

Soil water Logging had no detectable effect on soil moisture in the 20-80 cm depth range (Ouellet, 1979) as measured with the neutron probe.

Hydrogeology A network of 30 piezometers were used to measure ground water levels and movement (Rochette, 1971). It indicated some relation between water inputs and groundwater levels and that leakage was negligible.

Snow accumulation and melt The snow accumulation and melt rate measured in a 2 m wide path used as a standard snow course were compared to the ones obtained in a plot under the canopy (Naud, personal communication). The snow water equivalent measured in the plot was used to evaluate the melt coefficient of the degree-days equation (U.S. Army Corps of Engineers, 1956) for melt under the canopy and in the open after clear-cutting the site (Plamondon *et al.*, 1984b). These data were also used to compare melting rates between flat terrain and sloping land with different expositions.

The plot studies are necessary to explain and sometimes confirm the results of the catchment experiments such as the patch cutting on Ruisseau des Eaux-Volées. Calculations of potential changes of evapotranspiration after clearing, based on albedos above the forest and a clear-cut area (McCaughey, 1978a) and energy balance considerations (Walker, 1975), indicate a reduction of evapotranspiration between 11 and 28% (Ouellet, 1979). This confirms that streamflow modification following patch-cutting 31% of the superficie could not be detected. Due to the humid conditions of the site, the cutting of mature trees and the presence of vegetation after clear-cutting, the decrease of evapotranspiration is more likely to be under 17%. In this case, clear-cutting of 62% of the area would be necessary to increase streamflow by 5% which is the precision limit of streamflow measurements (Lee, 1970; Hewlett, 1971). These findings are substantiated by the soil moisture study (Ouellet, 1979).

USE OF THE INFORMATION AND THE RESULTS

The watershed experiment and associated studies were very instrumental in the education of undergraduate and graduate students. The basic hydrometeorological measurements have permitted the quantification of the water balance components especially the evapotranspiration term. Low and peak flows from small areas in that region are only available from the experimental watershed (Boisvert, 1970; Louchard, 1970). However, the greatest use of the data was from streamflow modelling as a learning tool or to improve water management.

The Thornthwaite and the SSARR models were applied to the watershed as a mean to study the relationship between soil water, topography, snowmelt and streamflow (Berraja, 1974; Berraja *et al.*, 1988). The Stanford IV model was modified and calibrated against the streamflow from five watersheds having a variable area, precipitation and topographic characteristics. The objective was to develop a mean to improve hydrologic extrapolation (Llamas *et al.*, 1980). The model was successful in simulating peak flows and yield volumes. Some adjustment factors correlated well with physical properties of the watershed. A guideline for estimating the initial value of the soil moisture storage index was proposed.

Streamflow from the experimental watershed was used to verify the accuracy of CEQUEAU model (Morin *et al.*, 1981) when applied to a small watershed and to evaluate the importance of the physical characteristics on the simulated flow (Morin *et al.*, 1982). The precise data on precipitation and streamflow from Ruisseau des Eaux-Volées were necessary to evaluate a method to improve the simulated discharge from a watershed (Cavadias & Morin, 1985). The method combines simulated discharges with two or more models. The results from CEQUEAU (Morin *et al.*, 1981) and a simple statistical model demonstrated the improvement of combined simulated streamflow.

The impact of patch cutting 31% of the catchment area was too small to be detected and therefore could not yield any useful information for the manager regarding the maximum permissible area that could be clear-cut without modifying water yield. The cutting was limited to the mature forest stands. Since 70% of the area was logged in 1943, it will be possible to harvest this second growth forest in 5 years. We expect the water regime to respond to this second treatment.

DIFFICULTIES

To make a success of the watershed experiment, it is recommended to express the objectives clearly (USNC, 1977) and to coordinate the research program but not to the extent that innovation and new ideas are squelched (Doolittle, 1973). The implementation of watershed research requires the collaboration of scientists in several disciplines (Pereira, 1959) as well as cooperation between research institutions and governmental agencies (Dils, 1957; Trimble, 1959; Toebes & Ouryvaev, 1970). The commitment of the Direction Générale des Ressources Hydriques du Ministère de l'Environnement du Québec and l'Université Laval has permitted to maintain the measurements of the basic hydrometeorological parameters. However, this cooperation was not sufficient. The objective to increase our understanding of watershed processes was not fulfilled because funding was curtailed. This is illustrated by the acid rain research program on Lake Laflamme watershed. Because of continuous funding and the commitments of federal agencies, Lake Laflamme yielded more basic knowledge of the hydrologic system in 8 years than Ruisseau des Eaux-Volées yielded in 20 years (Stein, *et al.* in this Symposium). Ten publications, eight thesis and about five reports were produced from the latter.

The condition of the forest limited the range of treatments that could be carried out during the first 25 years so the management objectives could only be part fulfilled.

It is difficult to maintain interest in a project over such a long period. Some over mature patches are affected by windthrow in watersheds 5 and 7, and finally there is a risk that the hydrologic characteristics of the control watershed change over time due to the mature state of its forest cover.

The Ruisseau des Eaux-Volées experimental watershed could not answer one of the most important questions of the 1970s in relation to logging. What was the impact of commercial clear-cutting on erosion and water quality? What was the minimum width of the green strip that should be kept along the water courses to protect water quality? Obviously, this type of study had to be carried out over different regions during commercial clear-cutting operations.

In the late 1970s, a watershed was needed to evaluate the effects of acid rain on aquatic and forest ecosystems. For the objectives of the acid rain program, it was necessary that this watershed include a lake. Thus, Lake Laflamme watershed located 5 km from Ruisseau des Eaux-Volées was instrumented for this specific need.

It must be recognized that any one watershed is not appropriate to answer all questions related to hydrology, ecology or land use. However, maintaining the watershed over a 20 year span has been most useful in forecasting the frequency of low and peak flows, assessing hydrological models, establishing the local water balance and educating water or watershed managers. The watershed approach should continue to be used but as an area for integrated studies and a new basin should not be instrumented to solve each new problem.

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Representative agricultural watersheds (PLUARG) in Ontario

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ABSTRACT The 1972 International Great Lakes Water Quality Agreement established the Pollution from Land Use Activities Reference Group (PLUARG) to determine pollutant inputs to the Great Lakes from nonpoint sources. Representative agricultural watersheds (<80 km^2) were selected to determine the effects of soil, land use, and management practices on ambient concentrations and stream loading rates of selected pollutants. Representative agricultural watersheds (11) were chosen by a systematic process that considered soil landscape factors, land use, and livestock distribution with some trial water quality monitoring. Detailed studies of stream flow quality/quantity and pollutant sources and pathways to surface and ground water supplies were conducted. Study results included: an improved extensive data set reflecting watershed processes; predictive capability for many nonpoint source pollutants; and a widespread awareness of soil and water degradation issues. Federal, provincial and research agencies have made extensive use of the information obtained in the development and implementation of new programs.

RÉSUMÉ L'Accord International sur la Qualité de l'Eau des Grands Lacs de 1972 a établi le Groupe Consultatif sur la Pollution par l'Utilisation des Terres pour déterminer l'entrée de contaminants dans les Grands Lacs en provenance de sources diffuses. Des bassins hydrographiques agricoles représentatifs (<80 km^2) furent sélectionnés pour déterminer les effets du sol, de l'utilisation des terres et des pratiques d'exploitation sur les concentrations ambiantes et les taux de décharge de certains contaminants dans les cours d'eau. Onze (11) bassins furent choisis par un procédé systématique qui considéra des facteurs de topographie, d'utilisation des terres et de distribution du bétail avec quelques essais de contrôle de la qualité de l'eau. Des études détaillées furent entreprises sur la qualité et le débit de cours d'eau ainsi que sur les sources de pollution et la distribution subséquente des contaminants dans les eaux de surface et souterraines. Les résultats de l'étude comprennent: des bassins hydrographiques; la possibilité améliorée de prédiction de plusieurs sources diffuses de contaminants; une importante conscientisation des problèmes de dégradation des sols et de l'eau. Des agences de recherche fédérales, provinciales et autres se sont beaucoup servis des informations acquises par le développement et la mise en oeuvre des nouveau programmes.

INTRODUCTION

The Canadian/U.S.A. Great Lakes Water Quality Agreements of 1972, 1978 and 1987 expressed the commitment of each country to restore and maintain the chemical, physical and biological integrity of the Great Lakes Basin Ecosystem. In 1972, a recognition of the lack of water quality data from which to estimate the inputs of pollutants from agricultural and other rural source areas led to the establishment of a Pollution from Land Use Activities Reference Group (PLUARG).

The PLUARG study plan outlined four main tasks, including assessment of the problem, inventory of land use activities, watershed studies, and lake studies. The watershed studies were described as intensive studies of a small number of representative watersheds, selected and conducted to permit some extrapolation of data to the entire Great Lakes Basin. Further, efforts were to be made to relate contamination of water quality which might be found at river mouths on the Great Lakes to specific land use practices.

The Canadian Agricultural Watershed Studies, a main focus within the watershed studies task, were developed in a three-phase program with the following objectives:

Phase I, Monitoring:

To measure the ambient concentration and loading rates for various potential pollutants that occur with agricultural land use.

Phase II, Detailed Studies:

1) To determine the effects of the soil, land use and associated practices on ambient concentrations and loading rates of selected pollutants from agriculture.

2) To derive information on the mechanics of transport and storage of these pollutants within the selected agricultural watersheds.

3) To develop relationships so that the information derived could be utilized in a predictive sense and extrapolated to other areas.

Phase III Remedial Measures:

To develop remedial measures where significant problems are identified.

This program was proposed and planned in 1973, with field work beginning in 1974. The monitoring phase continued through the 1977 spring runoff, while a number of detailed studies were carried out between April 1975 and May 1977. Results were integrated by the Task C Synthesis and Extrapolation work Group into a final Canada-U.S. Task C report, which was utilized in the development of the PLUARG report to the IJC (International Joint Commission, 1978). Separate reports on each of the activities of the Agricultural Watershed Studies were published in an IJC-PLUARG Technical Report Series (International Joint Commission, 1979), and a summary series of technical papers was published in the Journal of Environmental Quality, 1982.

WATERSHED SELECTION

Available background information with respect to variability of soil, topographic, hydrologic, crop/livestock distribution, and climate factors revealed that it was not practical to study all combinations of these factors. The need for a systematic approach to site selection was readily apparent. To facilitate the selection of representative areas, agricultural regions were determined by combining soil landscape data with agricultural crop/livestock distribution data.

TABLE 1 Generalized criteria for grouping soils by potential to transport pollutants. (Personal communication D.R. Coote, Land Resource Research Centre, Agriculture Canada, Ottawa, Ontario.)

Group	*Sub Group*						*Potential for Pollutant Transfer*	
	Profile texture			*Others*			*to surface water*	*to ground water*
	fine	*medium*	*coarse*	*shallow*	*organic*	*misc.*		
1	*	*	*		*	*	*high*	*low*
2		*					*moderate*	*moderate*
3		*	*	*			*low*	*high*
4		*	*				*low*	*low*
5	*	*	*				*high*	*high*

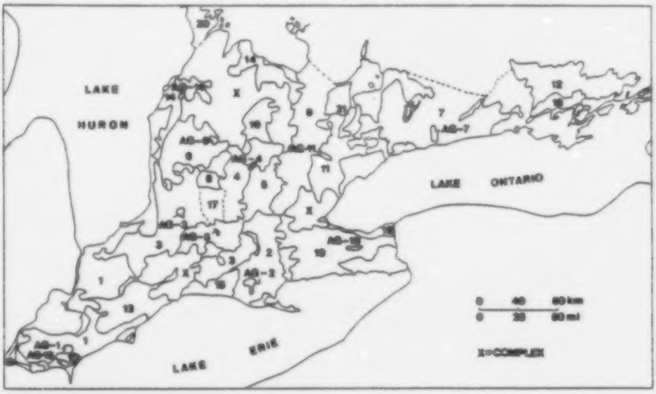

FIG.1 Twenty-one agricultural regions of the southern Ontario Great Lakes Basin and 11 selected agricultural watersheds.

A generalized division of landscape was determined by grouping soils into five major classes indicating probable potential to transport pollutants to surface or ground water (Table 1). A map (scale 1:250,000) of the study area illustrating the soil pollution potential was produced. Crop/livestock distribution data (Statistics Canada) provided a second level of input to the identification of agricultural zones. Maps (scale 1:1 million) were produced indicating the distribution of seven major crops and five livestock types. The maps derived from agricultural census data were overlaid on the soil group map. Twenty-one unique agricultural regions were identified (Fig.1). Watershed study sites (<80 km^2) representative of the defined agricultural regions were sought which would be large enough to have year round streamflow.

Trial monitoring of 16 watershed sites was initiated from May to October 1974 leading to the establishment of a final set of 11 suitable sites. The 10 agricultural regions not included in this study were considered to be areas of very low intensity agriculture or areas of specialized agriculture being adequately explored by U.S.A. studies.

DATA COLLECTION

Research in the agricultural watersheds included a number of monitoring studies to measure the ambient concentration and loading rates for rural nonpoint source pollutants and detailed studies to assess the sources and pathways of agricultural pollutants. The monitoring program included precipitation quantity, and stream flow quantity and quality. Further, an inventory of land use practices was conducted on the 11 representative agricultural watersheds. Detailed studies of pollutant sources and pathways were carried out for the most part in six of the watersheds included in phase II of the program.

Three of the watersheds had existing Water Survey of Canada flow gauges at their outlets. The remainder were instrumented by the Ontario Ministry of the Environment (OMOE) with Steven's A-71 water level recorders. Rating curves were established for each new gauging site and six sites were used for detailed pollutant source and transport studies, equipped with CAE automatic pumping samplers. All watersheds had a continuous-recording weighing rainguage, modified for operation in freezing weather.

Samples were collected in separate containers for heavy metals, total nutrients, soluble nutrients and other mineral parameters, pesticides, indicator bacteria, and suspended solids. The analyzed heavy metals included Cd, Cr, Cu, Pb, Ni, and Zn; and nutrient determinations involves total P, total dissolved P, soluble reactive P, dissolved ammonia, total Kjeldahl N, nitrate and nitrite N, and K. Many other variables were measured by the OMOE, including filtered Cl, Mg, Na, SO_4, and reactive silicates; and unfiltered C, inorganic C, Fe, Mn, and conductivity. Bacteriological parameters were also determined, as were in situ measurements of stream pH, dissolved 0_2, and temperature. Determinations were made by the Ontario Pesticide Residue Testing Laboratory for a number of pesticides including atrazine and endosulfan, and for PCB loadings.

Land-use data were collected at the watershed level by the Ontario Ministry of Agriculture and Food. Every farm in each watershed was visited, the operator interviewed, and statistics compiled on areas of each crop, quantities of fertilizers and pesticides used, types and numbers of livestock kept, and observations regarding management practices.

Soil surveys were carried out in six of the watersheds by the Ontario Soil Survey to improve the accuracy and extent of the existing soil survey data base. The six watersheds chosen for the soil survey were those in which detailed pollutant source and transport studies were undertaken. For the remaining watersheds, soils data were taken from published soil survey reports.

Average watershed gradient and stream density were obtained from maps, airphotos, and field observations. Estimates of tile drainage density were made by regional extension engineers from their records. An estimate of soil erosion potential was made from weighted mean soil loss calculated by applying the Universal Soil Loss Equation. Exposed streambank determinations were made by the Ontario Ministry of Natural Resources.

Much of the research that was conducted was field as opposed to laboratory related and relied heavily on stream water quantity and quality data. The length of time for which monitoring data (2 years) were collected was not sufficiently long to optimize the associated research investigations. A longer period of watershed monitoring (at least 5 years) would have been beneficial to the research investigations conducted in these watersheds

STUDY RESULTS AND USES

The PLUARG agricultural watershed studies have yielded an extensive data base from which our understanding and predictions of the role of agricultural land in determining water quality in rural streams have greatly improved. Further, a predictive capability was developed for identifying source areas of pollutants as well as for providing a rational approach to the development of remedial measures. Policy has been developed, management decisions have been made, and perhaps of greatest significance, the awareness of rural soil/water degradation issues in the Canadian Great Lakes Basin has risen significantly as a result of the watershed studies.

Technical Findings

Technical results from the PLUARG watershed studies were indeed voluminous and have been reported in innumerable refereed papers and in IJC technical reports as noted earlier. Suffice it to summarize a sample of the report/project topics to illustrate the range of findings:

a) on watershed characteristics -

- agricultural land uses, livestock and soils
- physical properties of soils
- geochemistry and hydrogeology

b) on precipitation and runoff -

- precipitation: quantity and quality
- streamflow: quantity and quality
- hydrological model

c) on contaminant sources and transport -

- soil erosion: locations and amounts
- streambank erosion
- sources and transport of sediments to the Great Lakes
- nitrogen movement in tile-drained clays and sands
- nitrogen loadings
- nitrogen transport and transformations
- nitrate enrichment of groundwater and subsequent loading to

surface waters
- contribution of phosphorus in surface runoff
- effects of livestock activities
- inputs to the Great Lakes from livestock enterprises
- pollution potential of cattle feedlots and manure storage
- pollutant transport to surface and subsurface waters
- sources, storage and transport of heavy metals

Federal Agencies

Federal government agencies concerned with Great Lakes water quality obtained quantitative data that indicated for the first time that nonpoint sources were contributing significantly to pollution of the Great Lakes. Of particular concern to Great Lakes environmental managers were the high phosphorus loads (3000 t y^{-1}) that were generated from agricultural land use. Significant agricultural contributions of nitrogen and pesticides (2.18 g $ha^{-1} y^{-1}$) were also observed.

In recognition of the continuing phosphorus problem in the Great Lakes the Governments of Canada and the U.S.A. signed an Annex to the 1978 Great Lake Water Quality Agreement which set target phosphorus loads for the Great Lakes and allocated load reductions to each country. Both countries agreed to submit plans for phosphorus reduction within 18 months.

Since that time, both U.S.A. and Canada have developed comprehensive management plans for the reduction of phosphorus to the Great Lakes. In both these plans, the management of rural nonpoint sources of phosphorus forms the dominant component of the programs. The data base and predictive capability developed in the PLUARG watershed studies was an integral part of the phosphorus management plan development.

The understanding of nonpoint source pollution processes that was obtained in the PLUARG watershed studies has impacted the International Joint Commission (IJC) and the Great Lakes Water Quality Agreement. In 1985, the Water Quality Board of IJC created a Nonpoint Source Pollution Subcommittee to deal principally with phosphorus control issues. Then in 1987, the Great Lakes Water Quality Agreement was amended to include for the first time a Nonpoint Source Pollution Control Annex.

Provincial Agencies

The provincial government agencies in Ontario have used information generated from the watershed studies extensively in program development. The watershed studies had identified that rural land use was significantly impacting water quality. Further, the agricultural watershed studies produced some quantitative data that suggested that conventional agricultural practices were also contributing to excessive soil erosion and general degradation of the soil resources. In recognition of these discoveries, provincial government agencies (Agriculture, Environment, Natural Resources, Transportation and Communications) established an interministerial committee to establish the relative significance and agency responsibilities regarding the soil erosion and sedimentation issues. As a part of these discussions, The Ministry of Agriculture and Food conducted a study to establish the economic losses to agricultural production that were associated with soil erosion. Subsequently the Ministry of Agriculture and Food initiated a financial incentive program to encourage farmers to implement soil and water conservation practices. More recently, a number of soil conservation advisors have been hired to provide technical assistance to farmers.

The Ministry of the Environment has initiated several programs in response to the PLUARG studies. First, an enhanced water quality monitoring program to better reflect individual storm events has been established for several major tributaries to the Great Lakes. The improved sampling and monitoring data have increased the reliabiltiy of tributary pollutant loading estimates.

The effect of livestock on local water quality in terms of bacterial contamination was recognized in the PLUARG watershed studies but not considered a threat to Great Lakes water quality. The Ministry of the Environment has responded by establishing an incentive program to farmers to improve manure storage and to control livestock access to streams.

Research Agencies

The extensive data base and understanding of the temporal and spatial variability of soil and water processes that was achieved in the agricultural watershed studies are used extensively by researchers and consultants. Researchers have used the data base to derive new predictive equations and to develop new and improved models. The GAMES model at the University of Guelph is a good example of this development.

Since the PLUARG watershed studies, a number of other nonpoint source pollution control studies has been initiated in Ontario. The main objective of these studies has been the implementation of soil and water conservation on the land. The concept of targeting erosion control to the most problematic areas, a recommendation of the PLUARG studies, has become an integral part of these erosion studies.

The watershed studies of PLUARG developed a number of simple prediction equations (e.g. for sediment and phosphorus) for estimating pollutant loadings. Private consulting firms involved in watershed management have made extensive use of these prediction equations to among other things target pollution prone landscapes.

SUMMARY

The agricultural watershed studies have provided an extensive data base from which to improve our understanding and prediction of the role of agricultural land in determining water quality in rural streams. They have provided insight into the problem of identifying source areas of pollutants from rural land. Further, the studies have provided information on which to base a rational approach to the development of remedial measures. The success of the studies can be related to the high level of coordination and cooperation that existed between the large group of managers and scientists participating in the program.

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Modelling the fate of atrazine in the Nissouri Creek watershed

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ABSTRACT A three-year field and modelling study (1984-87) on the transport and environmental fate of the herbicide atrazine was conducted in the Nissouri Creek watershed, a 30 km^2 agriculture watershed located within the Lake Erie drainage basin in southwestern Ontario. The objectives of the study were to investigate the use of a model (HSPF) to simulate the combined processes associated with the fate and movement of atrazine in an agricultural watershed and to evaluate the impacts of management practices.

This paper describes the reasons for the research and for selecting the modelling approach; the criteria used for the selection of the watershed, the pesticide, and the model; data needs; modelling highlights; the study findings; the difficulties encountered; and how this study could enhance the management of pesticides in Ontario.

RÉSUMÉ Le transport et la dynamique environmentale de l'herbicide atrazine ont été étudiés lors d'un projet de terrain et de modélisation d'une durée trois ans (1984-87) mené sur le bassin de Nissouri Creek, un bassin agricole de 30 km^2 localisé dans le bassin du lac Erié au sud-ouest de l'Ontario. Les objectifs de l'étude étaient d'évaluer le potentiel d'un modèle (HSPF) pour la simulation des processus associés au mouvement et à la dynamique de l'atrazine dans les bassins agricoles, et d'évaluer l'impact de pratiques agricoles.

Cette communication décrit le pourquoi de la recherche et de l'approche par modélisation, les critères utilisés dans la sélection du bassin, du pesticide et du modèle, les données requises, les points saillants de la modélisation, les résultats de l'étude, les difficultés rencontrées, et, enfin, comment cette étude pourrait améliorer la gestion des pesticides en Ontario.

INTRODUCTION

Pesticide use has risen substantially in Ontario during the past decade. In general, pesticides, when used properly and according to label, will cause minimal damage to the environment. Problems may arise when they are misused, stored improperly, or when spills or direct contamination occur.

The Ontario Ministry of the Environment (MOE) and other Ministries and agencies have concerns over the impacts on the environment from agricultural chemicals and industrial pollutants. With agriculture accounting for the majority of pesticides used in Ontario, the Ministry of Agriculture and Food

(OMAF) has great interest in better management of pesticides by farmers. Both MOE and OMAF consider it very important to understand, as much as possible, maximizing the benefits and minimizing the environmental impact of pesticides.

Extensive information on the chemical and biological characteristics of any given pesticide in use is usually available. The modes of contamination of waters with pesticides are also well understood. In addition, the factors which influence the pathways and transport of a given pesticide in the environment are well known. Relatively little research, however, has been done in the area of assessing the impacts of the combination of the above factors on the transport and fate of a pesticide on a watershed scale. It was felt by MOE and OMAF that the responsible use of pesticides in Ontario requires an inquiry into this area which could provide useful answers that would be helpful in the better management of pesticides in the Province.

In 1984, a three-year field and modelling study of the fate of atrazine in the Nissouri Creek watershed was begun. The study was carried out by the Ministry of the Environment (Water Resources Branch, Hazardous Contaminants Coordination Branch, and Laboratory Services Branch) in co-operation with the Ministry of Agriculture and Food (Soil and Water Management Branch, and Agricultural Laboratory Services Branch) and Beak COnsultants Limited.

The goals of the study were:

(a) To investigate the movement, transport and environmental fate of atrazine from agricultural fields to receiving waters using an appropriate mathematical model.
(b) To evaluate the practicality of using watershed modelling to predict the impacts of various management practices on atrazine losses.
(c) To recommend appropriate management practices to reduce atrazine losses from agricultural areas in Ontario.

As an additional by-product of the study, sediment and phosphorus movement and transport were examined.

WHY WAS THE NISSOURI CREEK WATERSHED CHOSEN?

The selected watershed for this study had to meet the following criteria:

(a) Small in size;
(b) Suitable for streamflow gauging and other instrumentation;
(c) Widespread application of atrazine;
(d) Absence of confounding factors such as significant point source discharges, impoundments, or non-agricultural land use activities.
(e) Representative in terms of soil types and agricultural activities to permit extrapolation of findings to other areas; and
(f) Historical records on hydrology, water quality, soils, land use and chemical applications.

The Nissouri Creek watershed met all the above criteria. This 30 km^2 watershed is located within Oxford County (Zorra Township) in southwestern Ontario.

The dominant soil types are Guelph Loam, Honeywood-Guelph Complex (silt loam), and Embro Silt Loam. The Guelph Loam is characterized by good drainage, moderate water holding capability, neutral reaction and lack of stoniness. The other two soils have finer particle sizes and display imperfect drainage which necessitated the installation of an extensive tile drainage system to alleviate the problem.

The main land uses in the watershed are: row crops (45.9%), hay and pasture (22.8%), cereals (12.2%), woods and unimproved lands (15.4%), and non-agricultural (3.7%).

The Missouri Creek watershed was one of 11 agricultural watersheds studied from 1974 to 1977 under the Pollution from Land Use Activities Reference Group Program (PLUARG) because it was considered to be representative of 990 km^2 in southern Ontario (Morley et *al.*, 1975).

WHY WAS ATRAZINE CHOSEN?

Over 400 pesticides, each with unique properties, are used in Ontario. For the purpose of this study and because of the very low levels expected in the water, the selected pesticide had to meet the following criteria:

(a) The pesticide must be widely used;
(b) It must be relatively persistent;
(c) It must be observed to move from treated fields to streams; and
(d) It must be frequently found in water.

One pesticide which meets the above criteria is atrazine. Atrazine, a S-triazine compound, is currently the most widely applied herbicide in Ontario being used mainly for the control of weeds in corn. In Ontario, atrazine persists in soils from one season to the next. In addition, this herbicide readily moves from fields mainly by surface water as well as via tile drainage.

WHY WAS THE MODELLING APPROACH CHOSEN? WHY WAS THE HSPF MODEL SELECTED?

Field studies along cannot serve to quantify the influence of the great number of variables which affect the transport and environmental fate of pesticides. Climate, watershed characteristics, soil type, pesticide properties, and management practices all have a profound influence on the mechanisms and magnitude of pesticide losses from a watershed.

Uncontrollable variations in the climate and the substantial resources required for experimental analyses of even a few possible management practices make simulation modelling an attractive alternative. Simulation provides a means to evaluate pesticide movement under a range of management practices while considering the modifying effects of climate.

The model selected for the study had to meet the following criteria:

(a) It must be able to simulated watershed hydrology, agricultural chemical transport, and instream processes;
(b) It must be able to simulate pesticide behaviour in detail including consideration of pesticide movement with sediment and in solution in surface runoff and subsurface drainage as well as the physical, chemical and biological reactions acting upon the pesticide;
(c) It should provide flexible subroutines for statistical analyses and risk assessment;
(d) It must provide utility modules for data transfer, tabulation, plotting, and time series transformations; and
(e) It must be easy to use and update.

One of the modelling tools that is available and which meets all of the above criteria is HSPF (Hydrologic SImulation Model-Fortran). HSPF is a comprehensive simulation model for predicting watershed hydrology, water quality, agricultural chemical transport, and risk assessment. The model benefited in its development from other models such as ARM, NPS, HSP, PTR, and Stanford Watershed Model. It represents the current state-of-the-art in continuous simulation of pollution from non-point sources.

HSPF uses information such as the time history of rainfall, temperature, and solar intensity as well as the characteristics of the land surface, soil type, land use, pesticide properties, and agricultural practices to simulate the processes that occur in a watershed. The flow rate, sediment load (erosion), and pesticide and nutrient losses are predicted. Instream modelling allows for the prediction of chemical concentrations in water.

The simulation produces a time history of water quantity, quality, and chemical transport at any point in the watershed. For ease of presentation and interpretation, flexible routines are provided for statistical analyses of the simulated output (Barnwell, 1982).

WHAT WERE THE DATA NEEDS?

The application of HSPF requires data on meteorology, water quality, atrazine properties, soil characteristics, land use and management practices.

The meteorological data required are: information on precipitation, potential evapotranspiration, air temperature, wind speed, solar radiation, and dewpoint temperature.

Loadings of suspended solids, total phosphorus, and atrazine were determined by monitoring and were used to compare and evaluate predicted loadings from modelling.

A number of special investigations were carried out on atrazine. First, the atrazine decay rate was determined using field plot studies. Second, the concentrations of atrazone and desethylatrazine were monitored in soil profiles. Third, stream bed sediment was sampled to assess its role as a sink or a source for atrazine. Fourth, the mode of movement of atrazine in the stream was examined to determine how it is partitioned between the aqueous phase and the solid phase. Fifth, laboratory tests were conducted to determine the potential adsorptive capacity of the soils for atrazine. Finally, two surveys of the watershed farmers were conducted to determine the rate, time, and areal extent of atrazine application.

Soil information was largely based on the Ontario Soil Survey by the Canadian Department of Agriculture (1961) and on a detailed soil investigation and a soil map produced by PLUARG in 1979. In addition, monitoring of soil temperature and moisture was conducted at five sites within the watershed to complete the description of the soil profiles within the watershed to complete the description of the soil profiles and to evaluate the accuracy of the model's soil water predictions.

Basic information on land use was obtained from the OMAF land use map of Oxford County. In addition, aerial surveys and ground truthing were conducted to prepare detailed maps of fields and crop type in place during the study.

WHAT WERE THE MODELLING HIGHLIGHTS?

The hydrologic processes modelled by HSPF are driven by weather input information. The input time series used in the study included three separate precipitation time series which were formed from three tipping bucket recordings. The model allows for spatial and temporal variation in rainfall for different land computational units. Hourly wind speed, air temperature, solar radiation, and daily evapotranspiration rate and dew point temperature were applied equally to all the units.

The temporal scale used in the simulation was based on one hour time step. Further, the watershed drainage system was discretized so that output information corresponded to the monitoring sites allowing direct comparisons between observed and predicted loadings.

Discretization of the watershed was based on slope, soil type and land use. Twenty-eight computational units were used for the 1985 simulation runs and 22 for the 1986. The watershed units were as small as a few hectares while the stream channels have contributing areas and lengths ranging from 170 ha and a few hundred meters to over 1000 ha and five kilometres (Beak, 1987).

WHAT HAVE WE LEARNED?

Findings Related to Field Investigations

The field programs were designed at the onset of the study and were further refined as required during the course of the study. Continuity was maintained throughout in terms of sampling and monitoring sites. The following are the findings related to field investigations:

(a) Atrazine application rates vary considerably from one operator to another ranging from 0.7 kg/ha to 5.8 kg/ha as active ingredient. Average application rates over the study period were consistent at approximately 1.85 kg/ha.

(b) The time of application ranges from late April (preplanting application) through May and June (pre and post emergent application) to OCtober (after crop removal).

(c) Atrazine was found in almost all tile water samples. The results indicate that atrazine is mobile in the soil matrix. Concentrations ranged from non-detectable to 85 µg/L.

(d) The data indicate that the presence of atrazine in ground water samples collected from piezometers is sporadic and highly variable in concentrations. Atrazine was detected in 44 of 153 samples collected. Concentrations ranged from non-detectable to 2.1 µg/L. The high value may be the result of a spill.

(e) Investigation of the movement of atrazine in the stream system indicated that the majority of atrazine is moving in soluble form and a minor amount (<1%) is associated with solids.

(f) Data on stream bed sediment collected during periods of most active atrazine use displayed levels near or below detection limit. The results indicate that stream bed sediment is not a major sink of atrazine.

Findings Related to Modelling

The HSPF model is a lumped parameter, deterministic model which is well documented with a user's manual and an application guide. The model contains several routines for data manipulation, management, summary, duration analysis, and plotting. The model allows for easy discretization and is readily expandable to large areas. Calibration of HSPF is time consuming and requires many computer runs, however, good output allows for a systematic stepwise approach. The most sensitive parameters are: infiltration rates, control zone soil depth, tile and ground water discharge rates, evapotranspiration rates, soil detachment rates, and adsorption isotherms. The following are some specific findings:

(a) Hydrologic verification was successful in terms of individual events and monthly and annual totals at three modelled stations. The largest discrepancies occurred during winter and during winter freeze and spring thaw periods. The errors are largely timing errors while the overall water balance is good.

(b) Observed daily sediment loads were available for about 50 to 60 days per year. Most of these observations were for runoff event periods. Daily predicted and observed loadings are within a factor of two. Predictions for late May, early June and October of 1985 and most of 1986 are good despite the fact that the range of observed daily loadings span four orders of magnitude.

(c) Observed phosphorus loads span four orders of magnitude during the study period. As in the case with soil loss, daily loadings are highly variable and recover to low values very quickly following an event. Predicted values were generally within a factor of two over the simulation period.

(d) Observed atrazine loadings span more than three orders of magnitude with total watershed daily loadings ranging from 0.004 kg to 17.1 kg in 1985 and from 0.001 kg to 1.97 kg in 1986. Loadings are highly variable and return to base levels a few days after an event. The rate of return to base levels, however, is not as rapid as with soil and phosphorus because a larger portion of atrazine transport is via subsurface routes in a soluble form.

Calibrated results are generally good, often within 10-20% of observed values. The study indicates that the vast majority of atrazine moves in soluble form through the subsurface tile system. Atrazine loss from the watershed ranged from 0.8 to 3.2% of that applied and is highly dependent upon the rate of precipitation shortly following pesticide application.

Findings Related to Evaluation of Agricultural Practices

The model can be useful for evaluating the impacts of various management practices and predicting the benefits of conservation methods. Such evaluation, however, requires a set of model adjustments to reflect the effects of various implementations. Because of lack of information on the impacts of various management practices on key model parameters in the watershed, the exercise was not a rigorous analysis of all possible practices, rather it was performed to demonstrate the practicality of using a modelling approach.

Six measures were evaluated: two structural (tile drainage and retention basins); two non-structural (no-tillage system and contour strip cropping); and two operational schemes (optimized timing of planting, and chemical application; and subsurface incorporation of atrazine). The following summarizes specific findings:

(a) The no-tillage and strip contour systems were found to be very effective in reducing soil loss and chemical transport.

(b) Tile drainage was found to be effective in reducing surface runoff and soil loss. On the other hand, while retention basins are effective in removing some of the larger particle sizes they are not effective in reducing the majority of phosphorus and atrazine losses as these chemicals are associated with fine particles (silt and clay) and frequently occur in a soluble form.

(c) Optimizing timing of planting, and chemical application; and subsurface incorporation of applied chemical were not found to be effective at controlling atrazine transportation in this study as these materials are associated with fine particles (silt and clay) and frequently occur in a soluble form.

WHAT WERE THE DIFFICULTIES?

Difficulties encountered during the study can be divided into a number of categories: financial, administrative, and operational.

Financial

A study such as the one described here is very costly. Costs are either direct and are related to Consultant's fees and purchase of equipment or they are hidden and are related to laboratory costs and staff time. Hundreds of samples were collected and analyzed for atrazine, conductivity, suspended solids, potassium, chloride, sulphate, total phosphorus, filtered reactive phosphorus, unfiltered total Kjeldahl nitrogen, ammonia, nitrites and nitrates. The average cost of an atrazine analysis is $50 whereas the average cost of analysis for each of the other parameters is $20. Availability of laboratory analytical capacity and budget area prerequisite condition before such a study could proceed.

Administrative

Any long-term study where many people are involved suffers from staff rotations and this study was no exception. During the course of the study a number of staff changes took place. Former staff take with them their accumulated experience and undocumented thoughts. On the other hand, new staff bring with them new ideas and may introduce new understanding of goals and objectives. Luckily in the case of this study, staff rotations did not result in any major deviation from the original goals and objectives. The exception to that was the placing of less emphasis on the investigation of the impacts of various agricultural practices on pesticide management. Time limitation made it difficult to carry a full assessment of this component which certainly deserves a more detailed treatment.

Operational

Operational difficulties encountered in this study are common in all comprehensive studies involving monitoring, analysis, interpretation, modelling and review. In fact, the study plan anticipated various kinds of problems and made allowance wherever possible. In the final analysis, our operational difficulties did not adversely affect the study results. To some extent the wealth of background data available for the study area aided in providing insight into general watershed characteristics and behaviour. Table 1 itemizes operational problems by type, impact and measures taken to compensate.

CONCLUSIONS

The study demonstrated that the modelling of the transport and environmental fate of a pesticide within an agricultural watershed, using a comprehensive

TABLE 1 Operational difficulties encountered

Type	Problem		Compensating Action
Monitoring	- vandalism	loss of equipment loss of data	- backup instrumentation - community education - secure instrument shelters
	- instrument error	inaccurate data	- quality assurance/control program - frequent recalibration and servicing
	- anomalous data	uncertain validity	- validate or reject based upon neighbouring site data and historical records
	- uncooperative land owners	missing pesticide use data	- estimation based on land use and overall average application rates
Data Handling	- large volumes of data		- necessitates data management system and routine data input and verification functions - large data storage capability required
Modelling	- model familiarization/ debugging	costs of professional and computer time	- established liaison with model developers and maintenance agency (U.S. EPA)
	- calibration/ verification	time and resource consuming	- systematic approach - sensitivity analyses - users manual guidelines - U.S. experiences
	- application	lack of data on model parameters related to land management	- relevant references - judgement

model such as HSPF, is a substantial task associated with financial, administrative, and operational difficulties. The study also showed that HSPF is capable of predicting watershed hydrology, water quality, and agriculture chemical transport. In addition, HSPF is capable of simulating a wide variety of management practices but its overall ability to accurately predict the impacts of these practices hinges on the model users ability to select appropriate parameter values.

One major objective of the study, to recommend appropriate management practices to reduce atrazine losses from agricultural areas in Ontario, remains largely unmet. It appears that a greater amount of effort has been expended to develop the HSPF model than to quantify the effects of various land management practices on its soil and agricultural chemical washoff parameters. If models such as HSPF are to be useful in the prediction of chemical losses from agricultural watersheds under various conservation practices then more research is required to quantify the effects of these practices on key model parameters.

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The Turkey Lakes watershed study

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ABSTRACT The Turkey Lakes Watershed Study (TLWS) was initiated in 1980 to evaluate the effects and processes of anthropogenic perturbations to Shield ecosystems. The TLWS was designed to provide an in-depth analysis of the biogeochemical processes that control pollutant-ecosystem interactions so that system models could be developed and validated. In particular, the stimulus for research in the TLW came from the desire to assess and understand the aquatic and terrestrial effects of acidic deposition.

The TLW is 1 of 5 hydrologically "calibrated" basins in eastern Canada that are devoted to process-oriented research into "acid rain" effects. They were selected to cover a wide range of climatic and hydrological conditions, deposition magnitudes, and terrain characteristics. The TLW represents moderately sensitive terrain receiving elevated but not maximum levels of acidic deposition. It is located on the Canadian Shield in the Algoma District of central Ontario, approximately 50 km north of Sault Ste Marie. The TLW is an undisturbed, completely forested basin (mixed hardwoods), 10.5 km^2 in area, that contains a chain of 4 lakes (5 distinct lake basins) which ultimately drain into L. Superior via the Batchawana R. For an Ontario setting, the basin has high relief and receives high levels of precipitation (ca. 1200 $mm\ y^{-1}$). Between 1976 and 1985, wet deposition of SO_4^{2-} ranged from 23 - 40 $kg\ ha^{-1}$.

Intensive hydrological and chemical monitoring within the TLW (20 permanent gauging sites) has permitted determination of water, ion, and nutrient budgets for both its terrestrial and aquatic components. The health and status of both the terrestrial and aquatic biological communities (species distributions, production, standing stocks, etc.) have been determined also. Specific hydrological research questions e.g. definition of water pathways during snowmelt, and the development of surface and sub-surface water quality as a function of water flux have also been considered. Hydrological and chemical models have been developed and validated using TLW data and these have been used to simulate watershed responses at other locations. The basin also has acted as a base for other related regional studies, and research is now branching to include assessment of the effects of other anthropogenic pollutants such as metals and toxic organics.

RÉSUMÉ Le "Turkey Lake Watershed Study" (TLWS) été mis sur pied en 1980 dans le but d'évaluer les processus et les effets des perturbation anthropogéniques sur le bouclier canadien. Le TLWS a été conçu de façon à fournir une analyse détaillée des processus biogéochimiques contrôlant les interactions polluants-écosystème afin de pouvoir développer et tester des modèles du système. Plus particulièrement, le stimulus à l'origine de l'étude dans le bassin de Turkey

Lake était le désir d'évaluer et de comprendre l'effet des précipitations acides sur les écosystèmes aquatiques et terrestres.

Le bassin de Turkey Lake est un des cinq bassins hydrologiquement "calés" dans l'est du Canada qui sont dédiés à la recherche sur les précipitations acides. Ces bassins ont été choisis de façon à représenter une large gamme de conditions climatiques et hydrologiques, de taux de déposition et de types de terrains. Le bassin de Turkey lake a une sensibilité modérée et reçoit des taux élevés, mais non extrêmes, de déposition acide. Le bassin est situé sur le bouclier canadien dans le district d'Algoma, au centre de l'Ontario, à environ 50 km au nord du Sault Ste-Marie. D'une superficie de 10.5 km^2, le bassin est recouvert d'une forêt de feuillus mélangés, et contient une série de 4 lacs (5 bassins lacustres distincts) qui se déchargent dans le lac Supérieur via la rivière Batchawana. Le relief est fort pour un site ontarien, et la précipitation annuelle est d'environ 1200 mm. De 1976 à 1985, les depôts humides de SO_4^{2-} varient de 23 à 40 kg ha^{-1}.

Une collecte intensive de données chimiques et hydrologiques sur le bassin de Turkey Lake (20 sites permanents de mesure) a permis de déterminer les bilans hydriques, ioniques et nutritifs des zones aquatiques et terrestres. L'état et la santé des communautés terrestres et aquatiques (distribution des espèces, production, populations, etc...) ont aussi été relevés. On a attaqué certaines questions de recherche hydrologique spécifiques telles que le cheminement de l'eau lors de la fonte, et la dynamique de la qualité de l'eau de surface et souterraine en fonction du taux d'écoulement. Des modèles hydrologiques et chimiques développés et calés grâce aux données du TLWS ont servi à simuler les réactions d'autres bassins. Le bassin a aussi servi de base pour différentes études régionales, et une nouvelle orientation de recherche est l'évaluation des effets d'autres polluants anthropogéniques tels que les métaux lourds et les produits organiques toxiques.

INTRODUCTION

During the 1970's, science and government became aware of the potential environmental impact of the long range transport of air pollutants (LRTAP). Concern focused on acid-forming pollutants, particularly SO_x, as several cases of surface water acidification and loss of fish populations were documented in Scandinavia, Canada, and the US. Atmospheric deposition of acids and other contaminants is a system-wide insult; thus, it is appropriate to use whole basin studies to evaluate biogeochemical processes controlling pollutant-ecosystem interactions. Understanding these processes is necessary for both the effective measurement of LRTAP effects and the development of models to confidently predict impacts over greater space and time. This paper describes the development of a study in the Turkey Lakes Watershed (TLW) located in central Ontario (Algoma District), and emphasizes the basin selection process, difficulties encountered, accomplishments, and overall impact in the context of the wider LRTAP research program.

Basin Selection

Recognizing that there exists wide variations in climate, magnitude of acidic deposition, and terrain characteristics throughout eastern Canada (i.e. that portion of the country affected by acid rain), a series of 5 research basins was selected in which intensive whole-ecosystem monitoring was or could be undertaken. Similarities and differences in responses to LRTAP observed among the basins provide insight into the dominating processes that occur at each location. Two of the basins (Experimental Lakes Area, north-western Ontario

near Kenora, and Muskoka-Haliburton, south-central Ontario, centred around Dorset) were established earlier to address the issue of lake eutrophication and already possessed substantial data bases suitable for calculation of ion budgets and assessment of LRTAP effects. The remaining 3 basins were specifically established for LRTAP studies, and included the TLW in central Ontario, north of Sault Ste Marie, Lac Laflamme in southern Quebec, north of Quebec City, and Kejimkujik in southern Nova Scotia. All of them were operating by the early 1980's. They cover the entire range in observed deposition, i.e. from <10 to >30 kg ha^{-1} wet SO$_4^{2-}$. The research emphasis in any individual basin tends to reflect its particular physical, chemical, and biological characteristics. Certainly, no single basin does or can address all aspects of atmospheric, aquatic, and terrestrial LRTAP research; however, when taken together, they provide insight into virtually all the questions being pursued during the current national assessment of acid rain effects.

The decision to establish a research basin in the Algoma region of central Ontario was motivated initially by 2 factors: first, a perceived need to fill a gap not covered by the other basins, i.e. investigate LRTAP effects under conditions of significant though not maximum deposition levels in a terrain of only moderate sensitivity; and second, a desire to utilize expertise in a truly integrated watershed study that was already resident in Sault Ste Marie at the Great Lakes Forestry Centre (Canadian Forestry Service, Department of Agriculture) and the Great Lakes Laboratory for Fisheries and Aquatic Science (Department of Fisheries and Oceans).

A systematic process was initiated to select the field site. Essential basin criteria included: (1) an undisturbed, interconnected, cascading lake chain progressing downstream from an headwater lake, (2) hydrological systems that were amenable to weir construction and accurate flow measurement, (3) geochemical conditions that were regionally representative, (4) location within daily commuting distance of Sault Ste Marie (maximum 50 - 70 km) and having reasonable access, (5) an intact, typical and representative, mature, homogeneous Great Lakes - St Lawrence forest, (6) a gradation in fish population characteristics within the lake chain, (7) self-sustaining fish stocks, and (8) and a salmonid population (brook and/or lake trout) within at least 1 of the lakes. It was assumed that if acceptable basin characteristics were found for fish, the characteristics of lower aquatic biota populations would also be "representative" of other lakes in the region.

By using the simplest logistical criterion (i.e. distance from Sault Ste Marie), approximately 100 potential candidates were identified on topographic maps. Consideration of existing information (mostly on fish stocks but also other geological and hydrological data) eliminated 70% from further consideration. The remaining basins were visually inspected to determine whether suitable forest conditions existed, and in the end, 8 specific candidates were sampled chemically and biologically to ascertain overall suitability. It turned out that the most restrictive criterion was the combination of basin access and the existence of an intact, mature forest since almost all bush access in the Algoma District has been gained by the construction of logging roads. Also, construction of logging roads usually resulted in substantially increased recreational usage of the lakes and sometimes cottage development; both of these factors reduced the attractiveness of a number of sites. Of the 3 acceptable sites left at the end of the selection process, the Turkey Lakes Watershed (Figure 1) was ultimately chosen as the best overall candidate. It is located approximately 50 km north of Sault Ste Marie, and, while this was near the outer limit of the distance criterion, it was truly remote and undeveloped, and access was gained at relatively low cost by re-establishing a road previously used to service a nearby but now abandoned fire-tower. The association of the road with the fire-tower rather than logging accounts for the relatively intact nature of the surrounding forest. The entire selection process took 8-9 months to complete.

BASIN DESCRIPTION

The TLW is 10.5 km^2 in area and fully contains the drainage area of a headwater chain of 4 lakes (5 distinct basins). It is located on provincial Crown land and is reserved for research purposes through cooperation of the Sault Ste Marie District, Ontario Ministry of Natural Resources. The terrestrial and aquatic resources within the basin are representative of the surrounding region of Algoma, although for Ontario, it does have high relief (290 m) and high annual precipitation (>1200 mm). Bedrock in the TLW is predominantly Precambrian metamorphic basalt (greenstone) with minor occurrences of granite; the overburden is composed of a 2 component glacial till varying in thickness from <1 m at high elevations to 1 - 2 m at lower elevations. There are also limited occurrences of extremely deep till sequences (up to 70 m) within bedrock valleys. The till mineralogy is more felsic than the underlying bedrock showing that this material was likely primarily derived from the large granitic intrusions that occur just north of the basin. Also, the till contains 0 - 2% $CaCO_3$ with higher concentrations generally occurring deeper in the profile and at lower elevations. This small but easily weathered component of the overburden is the primary factor contributing to the "moderate" sensitivity of the terrain and is a feature common to much of northern Ontario (Jeffries et al., 1986a).

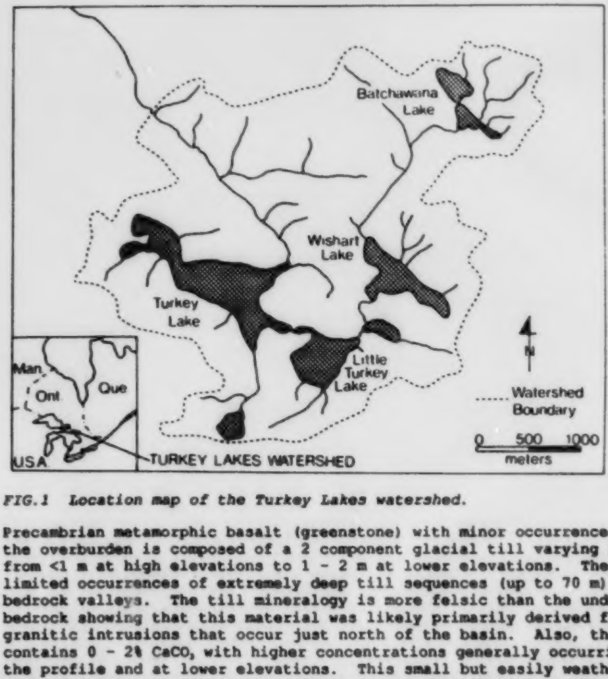

FIG.1 Location map of the Turkey Lakes watershed.

The rather angular drainage pattern (Fig.1) arises from structural control exerted by 2 intersecting regional fault systems. There are 20 fully instrumented streamflow gauging stations, most having artificial flow control structures. Fourteen of these are situated on first order headwater streams; the remainder are at lake outflows or further downstream on the major stream channel (Norberg Creek). Hydrological monitoring (like all other chemical, meteorological, and deposition monitoring) is conducted on a year-round basis.

The chain of lakes range from 5.8 ha (Batchawana L. South, see Fig.1) to 52 ha (Turkey L.) in surface area, and from 2.2 m (Wishart L.) to 12.2 m (Turkey L.) in mean depth. The relatively high precipitation causes the lakes to flush fairly rapidly; water renewal times range from 0.15 (Wishart L.) to 1.3 yr (Batchawana L. North). All of the lakes are dimictic with the exception of Wishart L. which experiences recurrent wind-induced mixing due to its shallowness. Dissolved oxygen depletion occurs in undisturbed bottom waters of all lakes except Turkey L; the hypolimnetic oxygen pool present in this the deepest lake of the chain is apparently large enough to prevent development of anoxic conditions.

There is a gradient in the major ion composition of lakes within the TLW, the most dilute waters occurring at high elevations. Calcium levels increase from 55 to 138 μmol L^{-1} down the chain. Sulphate is the dominant anion in Batchawana L. while alkalinity dominates in the lower lakes. Phosphorus is the limiting nutrient in these lakes; NO_3-N levels are relatively high (7.9 - 16.4 μmol L^{-1}) because the terrestrial basin exhibits low utilization of this nitrogen species. Seasonal and episodic variation in surface water composition can be large.

Batchawana L. contains no fish; however, fish communities in the lower 3 lakes (composed of 3 - 11 species) are typical of the Algoma region. The distribution of benthic organisms is primarily a function of lake depth and the presence/absence of fish rather than variations in water chemistry. Zooplankton species composition is similar across all lakes, and cyanophytes are the dominant algae throughout.

The forest is an uneven-aged, mature-to-overmature, old growth tolerant hardwood stand. The principal tree species are maples (90%), with lesser amounts of other hardwoods (9%, usually yellow birch) and various conifers (1%). Production is typical of forest at this northerly latitude (47°N). Foliar bioelement concentrations are generally similar to those observed at Hubbard Brook, New Hampshire. Further detail on the physical, chemical, and biological characteristics of the TLW can be found in Jeffries *et al.* (in press).

DISCUSSION

Research topics

The TLWS was intended from the outset to be multidisciplinary in nature, and the breadth of research conducted in the basin reflects this priority. Primary research responsibilities fall on several government agencies including the Great Lakes Forestry Centre (GLFC), the National Water Research Institute (NWRI), the Great Lakes Laboratory for Fisheries and Aquatic Science (GLLFAS), the National Hydrology Research Institute (NHRI), the Atmospheric Environment Service (AES), and the Ontario Ministry of Natural Resources (OMNR); various university researchers have also been involved (Queen's, Guelph, McMaster, Laurentian, Waterloo, Wilfrid Laurier). In order to coordinate activities among such a diverse group and maintain overall control of the study, scientific direction is provided by a Steering Committee composed of senior scientists from the participating agencies.

The TLW station for measurement of atmospheric deposition has been designated an official site in the Canadian Air and Precipitation Monitoring Network (AES). Both wet and dry deposition is measured (Sirois & Vet, in press). In addition, meteorology and bulk deposition are monitored by NWRI (Semkin & Jeffries, 1986a) and bulk deposition, throughfall, and stemflow are monitored by GLFC (Foster & Nicolson, 1983). Kelso & Jeffries (in press) estimated that annual SO_4^{2-} deposition has ranged from 23 (1980) to 40 (1978) kg ha^{-1} between 1976 and 1985. The average annual deposition level is therefore somewhat higher than was expected during the original planning of the study; however, this has neither hindered the attainment of objectives nor detracted from the usefulness of results. Extensive studies have been conducted on snowpack storage and release of pollutants, and the associated effects on basin hydrochemistry (Semkin & Jeffries, 1986b; English *et al.*, 1986). Finally, measurement of the deposition of synthetic organic compounds has been initiated (Johnson *et al.*, in press; Strachan & Huneault, 1984).

Extensive studies of water quality development have been conducted in the TLW primarily by GLFC, NWRI, and MHRI. These include description of streamflow generation and the factors affecting stream composition (Semkin *et al.*, 1984; Nicolson *et al.*, 1987), groundwater hydrogeochemistry (Bottomley *et al.*, 1986; Foster *et al.*, 1986), and lake chemistry (Jeffries *et al.*, 1986b). Episodic changes in surface water composition were addressed by Jeffries & Semkin (1983). Paleolimnolgical analyses of lake sediment cores have been conducted using diatom (Delorme *et al.*, 1986), metal profiles (Johnson *et al.*, 1986), and invertebrate remains (Johnson & McNeil, in press).

Aquatic biology research is primarily conducted by GLLFAS and has encompassed surveys of biological communities (Kelso *et al.*, 1982), evaluations of phytoplankton production (Collins *et al.*, 1983), benthic production (Dermott, in press), fish population production (Kelso, 1985), and factors affecting fish production (Kelso, in press).

Terrestrial studies have included extensive evaluations of soil physical and chemical characteristics (Cowell & Wickware, 1983), laboratory studies of soil responses to acidic deposition (Hern *et al.*, 1985; Hay *et al.*, 1985), element cycling in the forest ecosystem (Foster et *al.*, 1983; Foster & Nicolson, 1986), quantification of phytomass element concentrations (Morrison, 1983; Morrison & Hogan, 1986), and estimation of timber standing stock and production.

Finally, there has been extensive work to develop and validate simulation models for predicting stream hydrology and chemistry (Bobba *et al.*, 1986; Lam *et al.*, 1986). They have proven to be quite transportable having successfully simulated flow and chemistry from other watersheds. The models along with terrestrial watershed (Foster *et al.*, 1986) and lake mass budget studies (Jeffries *et al.*, 1986b) have also served to integrate many of the individual results into a broader picture. The overall integration of component studies still requires much future effort however. It should be noted that due to space limitations, this is an incomplete list of topics researched within the TLWS. Many other papers deal with such areas as stable isotope investigations, microbiology, additional lake sediment studies, geology/geochemistry, wildlife, forest classification, etc.

Difficulties

The most significant difficulties encountered during the life of the TLWS have been logistical, arising from the basin's remote location. Most of the problems have been solved, but at significant and continuing costs. The most important of these are fuelling and maintaining diesel generators to supply the electrical needs of the atmospheric monitoring station and the small field laboratory, and road maintenance (particularly snow plowing) to permit daily year-round access to the site. Accessibility during the peak of spring snowmelt can be very difficult but is nevertheless essential since there has been great emphasis placed on defining effects of the snowpack release of pollutants; thus, a small camp of "bunk house" trailers has been established to accommodate 6 - 12 field technicians for this short period of time. The distance of the basin from Sault Ste Marie also costs substantial time, i.e. that unproductive commuting time spent by field personnel. However, we believe that the quality of the ecosystem available for study in the TLW outweighs all of these problems.

Another potential difficulty is the multiple agency structure of the overall study. First, sharing of major logistical costs among the 3 principal participating agencies (NWRI, GLFC, and GLLFAS) has left the study vulnerable to cost-cutting by any one of them. While this has not been a major problem to date, it continues to be worrisome since the agencies are meeting these obligations using "soft" resources. Second, shifts in research priorities by different agencies could threaten the cohesive nature of the TLWS. The active role taken by the Steering Committee does much to promote interagency communication and maintain the harmonious nature of the independent, yet interdependent studies being conducted in the basin.

Accomplishments, impact, availability of results

Acid rain is a high priority research issue for all of the agencies involved in the study. From its inception therefore, the TLWS has been under pressure to produce information that is of immediate value in assessing local and national acidification effects. The study has been very successful in this regard as reflected in publication of well over 100 reports and/or papers covering all research components: atmospheric deposition, water quality development, geochemical process definition, aquatic and terrestrial biology, episodic acidification, simulation modelling, etc. Results were extensively cited in the most recent national assessment of acid rain effects on the Canadian environment (RMCC, 1986), and are being extensively used by water resource managers in the preparation of yet more up-to-date assessments that support bilateral negotiations for reduction in acid precursor emissions.

Three particular products attest to the scientific impact of the TLWS. First, at a time when the TLWS had been in existence for only 5 years, participating scientists presented and published 10 papers at the last major international acid rain symposium, the so-called Muskoka Conference in 1985 (Muskoka Conf. Proc. appear in Vol. 30 and 31 of Wat. Air Soil Pollut.). Second, a more important and thorough presentation of the wide-ranging research conducted in the basin will soon appear as a special volume of Can. J. Fish. Aquat. Sci. (21 papers in Vol. 45, Suppl. 1). Third, the Steering Committee decided early on that an inclusive reference list be maintained for all publications related to the TLWS. The Reference List contains a short summary of each entry and is available to anyone; it has served as a useful mechanism for disseminating knowledge of study findings among the greater scientific community. At the time of writing, the Reference List contains 113 entries.

Finally, if confronted with the same research need again, we feel confident that the research basin approach would still be adopted. Evidence of this is the continued operation of the TLWS, the current evolution of research activities to address the problems of NO_x, metals, and synthetic contaminants, and a new initiative to designate the site as a member of an international long-term integrated monitoring network.

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The status of research basin studies at Perch Lake, Ontario

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ABSTRACT The IHD study at Perch Lake was designed to test commonly used methods of estimating lake evaporation. Evaporation estimates from the water and energy budgets were to be used as standards. The budget approach required the establishment of hydrometric installation on all the streams entering and leaving the lake and a hydrometeorlogical observation network. The first water budget calculation revealed a significant groundwater input into the lake. The latter could be estimated by combining the energy and water budgets. A new objective was then added to test the reliability of commonly used methods of estimating groundwater inflow.

Perch Lake was chosen for this work for several reasons, the most important being the presence of radioactive substances, particularly the mixed oxide of radioactive hydrogen (tritium), which could be used as tracers for some of the studies. The hydrometric and hydrometeorlogical measurements were continued to the end of 1986. The basin drainage part of the IHD study continued after the decade ended and was extended further to include chemical and radiochemical transport in the surface and sub-surface waters.

The basin approach for this type of work, particularly that associated with the use of tracers, is a "black box" approach. It has the advantage and attraction of relative simplicity and cheapness because "bulk" parameters can be evaluated for use in modelling of basin drainage. There are disadvantages however. The parameters are site specific and lack generality. These types of parameters are most useful when the source of interest is distributed basin-wide but are of little use when modelling isolated sources, such as waste burial sites, which cover relatively small areas. In recent years we have tended to return to more fundamental studies of individual basin processes, as budget restraints have forced us to abandon the basin scale facilities.

RÉSUMÉ L'étude de Perch Lake, réalisée dans le cadre de la Décennie Internationale d'Hydrologie, avait pour but d'évaluer différentes méthodes d'estimation d'évaporation de lacs par rapport aux mesures obtenues par bilans hydrique et énergétique. Des stations hydrométriques ont été installées sur les charges et la décharge du lac. Un réseau hydrométéorologique a aussi été mis en place. Les premiers calculs faits en combinant les bilans énergétique et hydrique ont révélé un apport d'eau souterraine important. Suite à ces calculs, l'évaluation de méthodes d'estimation d'apport d'eau souterraine a été ajoutée comme objectif.

Le site de Perch Lake a été choisi pour plusieurs raisons, dont la présence de substances radioactives comme le tritium pouvant servir de marqueurs dans certaines des études. Les mesures hydrométriques et hydrométéorologiques se sont poursuivies jusqu'en 1986. La partie hydrologique comprise dans la Décennie Internationale d'Hydrologie a été

poursuivie après la fin de la décennie, et a été élargie de façon à inclure le transport de substances chimiques et radiochimiques par les eaux de surface et souterraines.

L'approche utilisée dans ce travail, particulièrement dans le cas des traceurs radioactifs, a été de traiter le bassin comme une boîte noire. Cette approche a l'avantage d'être simple et peu coûteuse car la modélisation hydrologique du bassin ne requiert alors que l'évaluation de paramètres moyens. Cependant, les paramètres ainsi obtenus sont spécifiques au site, et ont peu de flexibilité d'application. Ils sont utiles lorsque la source d'éléments chimiques ou radioactifs est distribuée à la grandeur du bassin, mais ne peuvent servir pour modéliser une source ponctuelle comme un site d'enfouissement. Depuis quelques années, la tendance a été un retour à l'étude fondamentale de processus individuels, les coupures budgétaires nous ayant forcé d'abandonner les installations qui nous permettaient de travailler à l'échelle du bassin.

THE STUDY

The Perch Lake Study had the initial objective to evaluate operational procedures and equations for estimating lake evaporation. The standards to be used for this evaluation were the estimates provided by the water and energy budgets. A third "standard" was a new method based on the use of tritiated water, i.e. water in which one hydrogen atom is replaced by its radioactive isotope, tritium with mass 3. Perch Lake contained concentrations of this tracer well above those arising from natural causes or atmospheric tests of nuclear weapons. Tritiated water vapours could be measured in the air above the lake using relatively simple techniques and it was certain that tritium found there had to have come from the lake.

It was this resource and the possibility of using tritiated water vapour as a tracer that led to Perch Lake being chosen for this study. As it happened, the radioactive method did not provide the measure of water evaporation expected but it did give a powerful set of data with which to test directly two-dimensional evaporation equations. These tests could not have been done any other way.

The water budget required that all the streams entering (there are 5) and leaving (there is one) the lake be gauged. This was a substantial undertaking because more than half the lake shore is swamp. Dikes had to be built to isolate the swamps and lead the drainage water to the gauging stations. Water levels were of necessity raised to allow sufficient drop at the weir plates. To prevent water by-passing the lake by running across from an inlet sub-basin to the outlet basin, the weak natural divide had to be augmented by another dike separating the two swamps. It was 1969 before the site preparation was complete and the study could begin.

THE RESULTS

The first water budgets established that the total of the annual surface inflows and direct precipitation together equalled almost exactly the annual surface flow at the outlet, i.e. the annual evaporation equalled almost exactly the net annual groundwater inflow. By combining the energy and water budgets, the net groundwater flow to the lake could be estimated with an unusually high accuracy, about 10%. Furthermore, since all piezometers in and around the lake showed that gradients were directed into the lake there was no groundwater flow out of the lake and the net flow in was also the total inflow by groundwater. Thus during the second half of the decade, a second objective had been added to the Perch Lake study, namely, to evaluate operational methods used to estimate groundwater flow using the combined water and energy budgets to give the "standard".

The study of the original objectives was successful. A wide range of one dimensional evaporation equations was tested, the use of evaporation pans intensively investigated, a method based on natural isotopes was tried and the use of tritiated water vapour concentrations in the air provided useful tests of some of the assumptions often made.

Evaporation equations based on the energy budget (e.g. Priestly-Taylor) were very reliable when the changes in heat storage were measured and used. In the absence of these refinements, these equations performed as poorly as the others based on a one dimensional aerodynamic model, i.e. equations of the type $E=cU(\Delta e)$ where U is the wind speed, Δe is the difference of vapour pressure between the surface and the atmosphere above the surface and c is a coefficient. The coefficient c was not constant but varied systematically by season. Perch Lake has a fetch of about 800 m but the tritiated water vapour profiles along the fetch showed clearly the internal boundary layer still growing at the downwind shore so that equations based on a one-dimensional model would not succeed. Similarly equations such as the Thornthewaite-Holzman which rely only on air gradients gave values for the evaporation strongly dependent on the measuring heights. Two dimensional models were tested using the tritiated water vapour concentration profiles as test data. Atmospheric turbulent diffusion of the ascending water vapour is inferred from the wind speed profiles. It was consistently overestimated near the surface and under-estimated higher up. The latter was undoubtedly caused by the high turbulence in the upper air layers because of the upstream flow over forest and rough terrain.

Two lines of enquiry were still unfinished when the decade ended and these were continued during the next couple of years. One was a comprehensive attempt to reduce errors in Class A evaporation pan estimates of lake evaporation for short averaging times (e.g. a month or less) by considering pan exposure and readily observable meteorological data. No satisfactory procedure could be found.

The other line of enquiry was to develop a model of lake evaporation that needed as input only the meteorological data collected at Class A weather stations, lake morphometry and an initial temperature profile in the lake. The latter could conveniently be taken as uniformly 4°C within a few days of spring breakup for lakes that are frozen during the winter. The model calculates the lake temperature profile throughout the remainder of the open water season. This project was successful and out of it came an operational model that gives good estimates of evaporation and temperature profiles for lakes varying in size from a few hectares to many square kilometres.

THE FOLLOW-UP

So far as I know, none of the findings of the study were put to use or incorporated with operational practices.

Why this should have been can never be known but one can put forward some suggestions as to possible causes. Here are a few:

(a) It is difficult to sustain systematic underlying research in any of the applied sciences where research is driven by specific applications and perceived needs usually inspired by economic, social or political forces rather than by desire to build up an organized branch of knowledge and theory. Research in the environmental sciences particularly goes by case studies; emphasis is on the specific from which generalizations are hard to discern and not thought to be much use.

(b) By the end of the decade, problems which had seemed so pressing at the start had been replaced by others even more pressing. This was especially so in the decade from the mid-sixties to mid-seventies during which interest shifted from water supply - too much (floods) or too little (droughts) - to water quality. Evaporation was one of the topics that lost its priority during the IHD. Interestingly enough one of the more pressing problems to replace it was deposition (= condensation) of the vaporous oxides of sulphur and nitrogen from the atmosphere to vegetation and water. But evaporation and condensation (i.e. deposition) are the same process - they differ only with respect to direction because the driving gradients are oppositely directed. The essential oneness of the two processes is hard to see while one focuses on the problems not on the science. Wit, said Madame de Stahl, consists of recognizing the similarities between things that appear to be different and the differences between those things that appear to be similar. The idea could be as useful to scientists as to wits.

(c) Probably not unrelated is the durability of those people who sponsor or of those who do not work. Research topics are often undertaken because of the interest of particular individuals. But people often do not stay in the same job for very long. Ten years is long compared to the turn-over time of individuals in a job and the job itself may be no more durable. If a person changes his job, the research may not continue or the results of the work sponsored by that individual may languish for want of a champion.

(d) Operational scientists and engineers tend to be conservation. This applies to operators of observational and monitoring networks as well as to those accepting commissions to calculate, to recommend or to evaluate on a consulting basis. One is less likely to be criticized for following a procedure that has been used customarily for the purpose than to follow a new one even though a research scientist has published a paper purporting to show the new method is superior to the old one.

This conservatism is easily defended. Decision making is a highly empirical art based as it is on what was successful before when similar circumstances arose. Decision makers want results which are comparable and consistent with those of the past. Accuracy has a negative value when its results are inconsistent with those of the past. The decision making process would have to be recalibrated to make use of the new results and this would, in effect, retain the status quo - better not to tinker with a system that works.

(e) As far as I am aware, there was no serious follow up to the IHD which had the express intention of determining what operational practices were in need of overhaul as a result of the findings of the decade and, if any, what changes should be made. These things do not just happen nor do they materialize spontaneously from the purely scientific colloquia which were held.

THE PRESENT AND FUTURE STATE

After the IHD ended, the facilities at Perch Lake were maintained for future work at the basin scale. Of particular interest were the behaviours of various airborne chemicals deposited more or less uniformly over areas of size comparable to research basin scales. However, enough of the needed resources to support such work could never be brought to bear and finally in 1987 under continuing budgetary pressure, the stream gauging facilities had to be discontinued. The only work at the basin scale that continues to be supported at Perch Lake is a small study of the application of remote sensing to the terrestrial and aquatic energy budgets.

Several considerations had to go into the decision to abandon the facilities at Perch Lake. Research at the basin scale with its long-time scales requires a heavy resource commitment that reduces flexibility in the use of manpower and equipment. At the same time increasing interest in waste management options required more study of individual processes at sites selected for the purpose.

A major advantage of basin scale research is the zero flux boundary. However, in most cases the lower boundary, bedrock or other aquiclude, is usually unknown or poorly defined so that models of basin response must always be calibrated. A necessary pre-requisite to a future successful program of basin scale research will be a cheap reliable method for identifying and mapping elevations of prominent stratigraphic units. Pulsed radar seems to be a method worth developing for this purpose and we have been encouraged by preliminary experiments made at Perch Lake. However, again we have not been able to find the necessary resources to pursue such work at the intensity required.

I find it difficult to believe that we will one day find it practical to model basin behaviour by synthesizing the basin from its component processes. Even if we can I doubt we would want to but at least as an intermediate if not a final step I would hope we could model basin behaviour from information that can be gathered from remote sensing, maps, bedrock elevations and the weather from a nearby weather station. To achieve this without calibration we are going to have to learn how to group processes and how to group process controlling variables to create useful bulk parameters and bulk process descriptions. This is equivalent to developing a theory of basin behaviour that looks at basin behaviour as a whole or as a system rather than the sum of its many parts. That such a theory exists is at present a matter of faith but I would be surprised to find complete chaos rules at this level of organization of natural systems.

To reach such a goal requires a commitment to an approach at the same level of organization, i.e. more between basin studies rather than more within basin studies.

In my view there is a need for strong institutional leadership because for reasons we have discussed above the subject has as yet no internal direction and drive.

COMMENTS

During the lifetime of the study (1969-1987), field work in the Perch Lake and adjacent basins has provided research material for over 50 graduate and postgraduate theses.

The operations in the progress during the study have provided practical instruction to two annual course credit field schools from the University of Waterloo (Departments of Earth Sciences and Geography).

A complete compilation of all the work done during the IHD has been published in a 2-volume report (ed. P.J.Barry (1975) and a summary report was given by Barry and Robertson (1975)). Work going on in the years immediately following the IHD have been described in 2 reports (ed. P.J.Barry (1977) and (1979)). The extensive work done on evaporation pans was presented by den Hartog and Robertson (1977). A users' guide to the Lake Energy and Evaporation Model (LEEM) appears in a report by Barry and Robertson (1983). The 11-year water and energy budgets for Perch Lake have been given by Barry and Robertson (1985).

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The Wilson creek experimental watershed study

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ABSTRACT In 1957, the Wilson Creek Watershed was selected as a study site for flood and erosion control on streams originating on the Manitoba Escarpment. For 30 years meteorological and hydrologic data were gathered and the watershed was studied to determine its runoff characteristics. As well, works such as headwaters storage, bank stabilization, vegetative cover and gradient control structures were experimented with. It was hoped that through a combination of basic research and experimental physical works in the basin's headwaters, that solutions could be found to flooding and siltation problems which affected agricultural lands below the escarpment.

Throughout its lifespan, the Wilson Creek project was run by a committee composed primarily of government officials. Direct funding was provided by various federal-provincial cost-sharing agreements such as the Northwest Escarpment Agreement, Canada-Manitoba Agricultural and Regional Development Agreement and Canada-Manitoba Value-Added AGreement on Crops Production. In addition, technical expertise and manpower were provided on an as-required basis by various federal and provincial departments and agencies. This administrative structure, while it worked reasonably well, had two major shortcomings. Firstly, there was no one agency with ultimate responsibility for the project as a whole. Hence there were some difficulties with long-term planning and carrying out integration and analysis of research efforts and results. Secondly, there was no long-term guarantee of funding. In many instances the project depended on the departmental generosity of committee members, and, from time to time there was need to "scramble" for funds from whatever sources were available. p Despite those administrative difficulties, the project's accomplishments were considerable. In large measure, the original objectives were fulfilled; in addition, the watershed was designated as one of Canada's research basin contributions to the International Hydrologic Decade in 1965, and, the basin served as a teaching aid and living laboratory and formed the basis for a large number of student theses and published papers and workshops. Moreover, many of the findings from this work, particularly pertaining to headwaters storage, escarpment runoff, groundwater regimes and erosion control and alluvial fans siltation problems, have been put to practical use by Manitoba water management officials as well as by local municipalities and Conservation Districts.

If faced with similar research needs as existed in 1957, it is the opinion of the authors that a research/experimental basin approach would again be appropriate. In order to be more assured of success however, such a project would be included in the regular programming activities of a federal or provincial department to ensure long-term continuity from both funding and technical perspectives.

RÉSUMÉ En 1957, le bassin de Wilson Creek a été choisi comme site d'étude sur la réduction de l'érosion et des inondations dans les cours d'eau provenant de l'escarpement du Manitoba. Depuis 30 ans, on y a recueilli des données météorologiques et hydrologiques, et étudié le bassin même de façon à cerner ses caractéristiques d'écoulement. En parallèle, on a évalué l'efficacité de différents ouvrages tels que l'emmagasinement des eaux de tête, la stabilisation des berges, la couverture végétale et le contrôle du gradient hydraulique. On espérait, en combinant la recherche de base à l'essai de méthodes de contrôle sur la région de tête du bassin, trouver des solutions aux problèmes d'inondation et de sédimentation qui affligent les terres agricoles en aval de l'escarpement.

Durant son existence, le projet de Wilson Creek a été dirigé par un comité formé surtout de représentants gouvernementaux. Les argents de fonctionnement provenaient de divers programmes fédéraux-provinciaux à coûts partagés tels que le "Northwest Escarpment Agreement", l'Entente Canada-Manitoba sur l'Agriculture et le Développement Régional, et l'Entente Canada-Manitoba sur la Valeur Ajoutée des Productions Agricoles. De plus, personnel et expertise étaient fournis au besoin par diverses organismes et ministères fédéraux et provinciaux. Cette structure administrative, bien que fonctionnelle, présentait deux lacunes. Premièrement, aucun organisme n'avait la responsabilité globale du projet, ce qui a causé des problèmes au niveau de la planification à long terme, de l'intégration des efforts de recherche, et de l'analyse des résultats. Deuxièmement, Il n'y avait aucune garantie de financement à long terme. A plusieurs occasions, le projet n'a survécu que grâce à la générosité des organismes représentés par les membres du comité, et de temps à autre, il fallait courir après les fonds.

Malgré ces problèmes, les réalisations du projet sont nombreuses. Les objectifs originaux ont été atteints en large part. Le bassin a été aussi inclus comme bassin expérimental dans le contribution canadienne à la Décennie Hydrologique Internationale en 1965. Enfin, le bassin a servi de support pédagogique et laboratoire vivant, et est à la base d'un grand nombre de thèses d'étudiants, de communications scientifiques et d'ateliers. Plusieurs des résultats de ces travaux, particulièrement en ce qui concerne l'emmagasinement des eaux d'écoulement, les caractéristiques d'écoulement, les régimes phréatiques, la réduction de l'érosion, et la sédimentation des plaines d'alluvions, sont utilisés en pratique par les organismes manitobains de gestion des eaux, de même que par les municipalités et les district de conservation de la région.

Si les mêmes besoins de recherche qu'en 1957 se reproduisaient présentement, il est de l'opinion des auteurs que l'approche par bassin expérimental serait encore appropriée. Cependant, pour mieux en garantir le succès, un tel programme devrait être incorporé aux activités régulières d'un organisme provincial ou fédéral afin d'assurer une continuité de financement et d'aide technique.

INTRODUCTION

One of Manitoba's most significant physiographic features is the Manitoba Escarpment. This escarpment, which was once the western shore of Glacial Lake Agassiz, runs in a northwesterly direction from south of the Canada-United States boundary to near the Saskatchewan River. It is composed of four major sections; the Pembina Hills in the south and the Riding and Duck Mountains and Porcupine Hills progressively northward. Vertical differentials between the plateau-like uplands and the former lake bed are in the order of a hundred metres in the Pembina Hills and up to 400 metres along the eastern slopes of

the Riding Mountain. It is this latter area which provides the setting of this paper.

Geologically, the Riding Mountain Escarpment is composed of a series of shale strata overlain by a mantle of glacial till. The shale layers are highly fractured, interbedded with bentonite seams and are highly erodible. In geologic terms, this area is very young and the most actively eroding in western Canada.

The escarpment area itself is approximately six kilometres wide and is characterized by deep, steep ravines cut into the till, bedrock shale and beach deposits. Runoff is very rapid and heavily sediment laden. At the base of this very steep section, land slopes abruptly become much milder and the streams lose much of their sediment-carrying capacity. As a result, an almost continuous deposit of reworked alluvial material has formed along the escarpment. Prior to settlement, runoff emerging from the steep slopes discharged onto these alluvial deposits creating a series of bogs and peaty swamps. These held the water and slowed its migration into the better- defined streams draining into the Manitoba lakes, the remnants of glacial Lake Agassiz.

As agricultural development proceeded, land was broken further and further up the slope of the escarpment. As the breaking progressed a demand soon arose for land drainage. Areas that once were tamarack swamps were reclaimed and over the years large trunk drains were installed with more and more laterals leading into them. As more land was cleared the local runoff was quickly added to the ditches and streams and this runoff combined with the runoff arising on the escarpment often produced devastating summer floods. The flood waters swept across the agricultural land scouring out gullies and leaving behind tremendous volumes of loose shale, logs, brush and other debris. This material clogged channels, bridges and other structures and forced water to flow across roads and fields, resulting in erosion, silt deposition and crop destruction. In consequence, maintenance of the drainage systems soon became a serious recurring drain on the financial resource of the municipalities. Drainage ditches which were cleaned out one year were completely filled with shale deposited by flood waters the following year, or sometimes during the same year.

Very serious floods in 1947 and 1953 caused a tremendous amount of damage along the base of the Riding Mountain and northward along the Duck Mountain and Porcupine Hills. Local pressure resulted in a Federal-Provincial-Municipal agreement to carry out flood control works along the Riding and Duck Mountains. The majority of the works were double-dyked floodways which carried the escarpment water through the agricultural land into the main natural waterways then to Dauphin Lake and Lake Winnipegosis.

It soon became apparent that this method of reducing flood damage was extremely expensive and more attention had to be paid to the headwater areas of these streams. Accordingly, in 1957, the Federal-Provincial Committee on Headwater, Flood and Erosion Control[1] was established to investigate headwater solutions to the flooding and erosion problems. The Committee consisted of representatives from both the Federal and Provincial Governments and covered a wide range of disciplines, such as, forestry, soils, meteorology, engineering, hydrology and agriculture.

THE EXPERIMENTAL WATERSHED APPROACH

The Committee's terms of reference directed it to examine the role that the headwater areas of escarpmental streams play in downstream flooding and erosion problems; and, to determine if deterioration in the vegetation in the headwater areas was contributing to an apparent increased runoff. In addition, the Committee was directed to examine and construct headwater measures which would reduce flooding and erosion. Recognizing the lack of basic hydrological data in the headwater areas, the governments also charged the Committee to obtain information with respect to hydrology and meteorology. Hence, the experimental watershed approach was dictated by the Committee's Terms of Reference, which reflected the perceived success at that time of the research basin approach in the United States; particularly in the Wasatch Mountains in the State of Utah.

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[1] Commonly referred to as the Headwater Control Committee.

In selecting an experimental watershed to study, the Headwater Control Committee focused on the major problem area, the Riding Mountain portion of the Escarpment near McCreary, Manitoba. The Wilson Creek Watershed, located just west of McCreary, was selected because it was representative of the problems to be dealt with on the over 60 streams that rise on the Manitoba Escarpment as a whole, and, was of a size that the experimental work could be readily undertaken and the necessary hydrological and meteorological measurements obtained. The watershed lies almost entirely within the Riding Mountain National Park and drains an area of 22.8 square kilometres (Fig.1).

During the initial stages of the project consideration was given to using an adjacent watershed, that of the McKinnon Creek, as a control basin against which remedial measures in the Wilson Creek Watershed could be compared. This idea was ultimately rejected as being too purely research oriented and hence only the Wilson Creek was monitored.

TOPICS RESEARCHED

During the 30 years of the experimental watershed project a variety of research endeavours were undertaken. Precipitation and streamflow data were collected; field scale laboratory experiments relating to bank stability, sediment transport and channel hydraulics were performed; and, the watershed was used as a classroom for University courses and post-graduate work as well as the location for workshops on stream processes organized by Dr. Robert Newbury for various government agencies.

Specific topics researched in the watershed

Rainfall-Runoff Relationships

Initially, the major lack of data was in the relationship between rainfall and runoff. Therefore, a comprehensive network of rain gauges and stream gauging stations was installed. In addition, instruments to measure other hydrometeorological parameters such as soil moisture, groundwater flow and evaporation were also located in the watershed. Data collected from those installations was used to develop flood frequency relationships, estimate the effect of soil moisture conditions on rainfall runoff and indicate the influence of the escarpment on precipitation. These research findings are currently being used by Provincial officials to predict potential flood conditions and hence facilitate early warning procedures along this section of the escarpment.

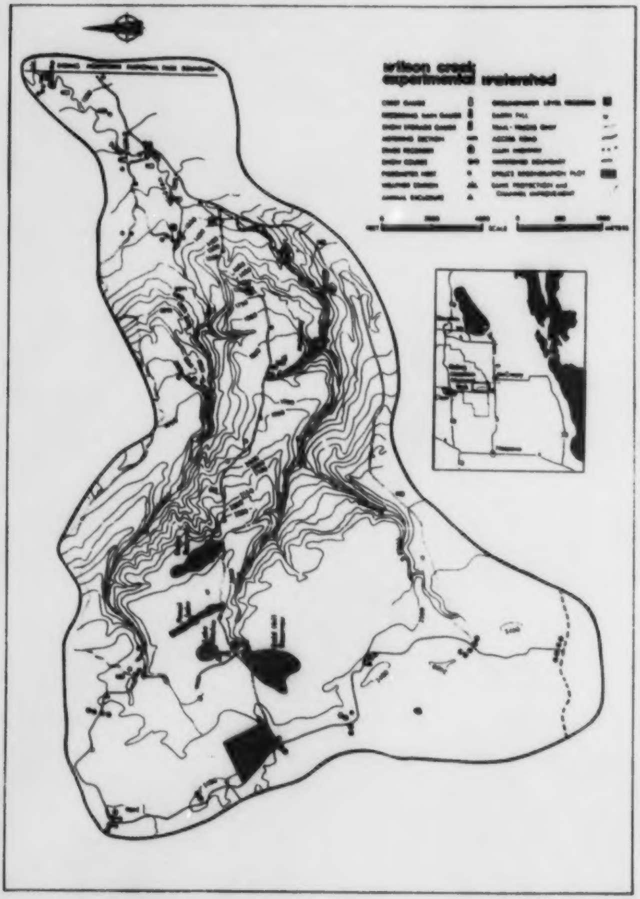
wilson creek
experimental watershed

FIG.1 Location map of the Wilson Creek watershed.

Groundwater

A large number of piezometers and instrumented wells were installed. These were used to examine groundwater movement in the watershed and to evaluate the interaction between groundwater and streamflow. In addition, new techniques for identifying the groundwater components of streamflow were developed. These techniques may have widespread applications in determining the movement of contaminants in groundwater.

Sediment transport

It was considered very important to obtain an understanding of the sediment production characteristics of the watershed. Review of available sediment samplers indicated that they would not be adequate for measuring the movement of rolling and saltating shale sediments in Wilson Creek. Accordingly, a small sediment trap was built and the deposited material periodically cleaned out and measured. In addition, measurements were made of the amount of sediment deposited in the drainage ditch that leads the runoff from the Park boundary to the Turtle River. By combining these data with streamflow records, the relationships between discharge and sediment load were investigated and mean annual sediment discharges estimated.

Headwater storage

One of the obvious methods of reducing flood peaks and the amount of sediment carried by the stream is the construction of headwater detention basins. After a comprehensive examination of the upper portions of the watershed two reservoir sites were selected and earthfill dams constructed. Each was equipped with an ungated corrugated metal culvert and a grassed spillway. Through measurement of reservoir stages, flood routing studies were carried out to estimate the reservoir's impacts on downstream flows. In addition, comparisons were made of the costs of headwater storage versus the benefits which would result. These indicated that, because the reservoirs can only control a relatively small portion of the drainage area, headwater storage is not likely an economically feasible flood damage reduction option. It should be noted that recent experience suggests the benefits assumed during the Wilson Creek work were underestimated and hence the economic viability of headwater storage should be revisited.

Channel stabilization

As noted earlier, streambanks crossing the Escarpment are very steep and composed of exposed, highly erodible shale. In looking for ways to reduce downstream sediment deposition, experiments were carried out to determine if and how these shale banks could be stabilized. Various rock riprap and timber crib works were put in place and their effects monitored. Unfortunately, the record flood of 1975 washed away all these works.

Alluvial fans

Studies of the Wilson Creek energy profile indicated considerable instability in the alluvial fan reach. It was concluded that connecting the man-made drainage channels to the natural stream emerging from the escarpment had steepened the energy gradient sufficiently to cause extensive erosion in the fan reach. Subsequent sediment studies and comparison of 1920's and 1980's aerial photographs indicated that approximately 75 percent of the Wilson Creek sediment load derived from the fan area and only 25 percent came from the escarpment itself. To see if the energy profile in the fan could be stabilized several low rock weirs were built and upstream and downstream cross-sections were monitored for change.

Miscellaneous

In addition to the foregoing, a variety of other studies were carried out in the Wilson Creek Watershed. Included, was examination of the effects of animal browsing on vegetation; estimation of the impacts of vegetation, or vegetation regeneration, on runoff; botanic studies of the vegetative history of the watershed, including pollen surveys of a small headwater lake, Lake Ritchie; and, examination of channel hydraulics by sudden release of water stored by a beaver dam.

DIFFICULTIES IN ACHIEVING THE OBJECTIVES

The major and overriding obstacle to the success of the Wilson Creek Experimental Watershed Project was the lack of a long-term commitment. The reason for this stems from the fact that the project was conceived and initially funded under the federal-provincial Northwest Escarpment Agreement. As a result of this "cooperative venture" approach no lead agency or department with on-going funding and program management responsibilities was ever identified.

When the Agreement terminated, well before the necessary data base had been collected, the Headwater Control Committee was forced to seek alternative funding. Two such sources were the Canada-Manitoba Agricultural and Regional Development Agreement and the Canada-Manitoba Value-Added Agreement on Crops Production. In addition, and particularly during the latter years of the project, members of the Committee had to provide their own time and as available, that of their staff. Of particular importance were the contributions of the Water Resources Branch of the Manitoba Department of Natural Resources and the P.F.R.A. These made possible the retention of a field supervisor, Mr. J. E. Thomlinson, for the entire life of the project.

The lack of commitment was also manifested in the experimental and research efforts carried out in the watershed. No long-range plan with specified goals and assigned implementation responsibilities was developed. Rather, initiatives were somewhat ad hoc and based on the interests and priorities of the individuals involved. As a result there was often a lack of continuity as membership on the Headwater Control Committee changed, or as individual researchers moved on before their studies were completed. In addition, the project suffered from the lack of a formal review process whereby "peer review" on a regular basis would have helped to insure that the experimental work was timely and useful given the advances being made in hydrology at this time.

Implicit in these shortcomings was the lack of a formal mechanism for data analysis and study. Again, due to their commitment and dedication, Committee members and member agencies undertook analyses as staff time permitted. As well analyses of the watershed were undertaken by many graduate students for graduate and post-graduate theses. Hence despite a lack of long-term commitment, the accomplishments were significant as noted in the next section.

ACCOMPLISHMENTS

The accomplishments of the Wilson Creek Experimental Watershed Program can be broken into two categories. The first consists of those accomplishments directly related to the original Terms of Reference, while the second includes the program's influence on the understanding of hydrologic sciences and water management as they relate to the Manitoba Escarpment. Highlights from both categories will be briefly discussed.

The major accomplishment of the Wilson Creek Program is that it did indeed provide answers to the questions posed at the outset. Some of these answers are merely affirmations that no action can or should be taken. For instance, it was shown that there are no undue changes occurring in the headwaters and, that while technically feasible, headwater storage would, for major flood events, result in only modest peak reductions in downstream reaches. Other answers are directly applicable to solving problems not only in the Wilson Creek basin, but along the entire escarpment. The most significant of these was the determination that the bulk of sediment does not originate on the escarpment but rather from erosion of the alluvial fans. Remedial measures in the form of low-head gradient control structures were tested and found effective during program activities, and are currently being utilized by a number of municipalities and conservation districts to reduce their drainage maintenance costs.

The accomplishments in the second category are quite varied. They include the development of a comprehensive publicly available hydrologic data base where none existed before. This data base, plus the remaining data-gathering network, have been incorporated into operating water management practices. For example, soil moisture and rainfall-runoff data from the Wilson Creek basin are the basis of a regional flood-forecasting system developed by the Manitoba Water Resources Branch. In addition, the groundwater studies have provided a better understanding of the recharge characteristics of the McCreary Aquifer, the Town of McCreary's water supply source.

The Wilson Creek program has also played a significant role in furthering the understanding of the hydrologic sciences both locally and internationally. In 1965, it was designated as Canada's first research basin contribution to the International Hydrologic Decade. It has also served as a teaching demonstration area and been the basis for a large number of graduate and post-graduate theses for students from the University of Manitoba. Moreover, the activities in the Wilson Creek Watershed have heightened the awareness and understanding of hydrology and water management of local and regional residents.

IMPACT ON THE UNDERSTANDING AND MANAGEMENT OF WATER RESOURCES IN CANADA

The understanding of watershed mechanics has been enhanced through the Wilson Creek Experimental Watershed. This has certainly impacted on the understanding and management of water resources in Manitoba and to a lesser extent in Canada. As noted in the previous section, escarpmental watershed management in Manitoba is now more focused on preserving or rehabilitating alluvial fans at the base of the Escarpment than on attempting headwater solutions. This results directly from findings at Wilson Creek.

The understanding of flood runoff events along the Manitoba escarpment has been greatly enhanced by the project. The Wilson Creek Watershed remains the only area where a significant hydrometeorological data base exists. It has been found for flood events that the technology learned at Wilson Creek can be transferred to other locations along the escarpment.

The many workshops on stream processes which Dr. Newbury has conducted in the watershed have added to the understanding of water resources by many disciplines from across Canada and the United States.

In addition, the familiarization seminars sponsored by the Canadian Committee for the International Hydrologic Decade and held across Canada used many examples from Wilson Creek to explain hydrologic phenomenon.

AVAILABILITY OF RESEARCH FINDINGS

The research findings derived from the Wilson Creek Program are readily available to all interested parties. The most widely-distributed documentation of results is the "Summary Report of the Wilson Creek Experimental Watershed Study 1957-1982" (Committee on Headwater Flood and Erosion Control 1983). This report, forwarded to several hundred interested persons, libraries, government agencies, etc., summarized all pertinent research efforts and their results to that date. In addition, it includes a chronology of activities and studies as well as listings of references.

In addition to the Summary Report, a series of Annual Project Reports documenting activities in the watershed, physical conditions, hydrometeorological data, etc., were prepared during the life of the program. Copies of these reports are available through the Manitoba Water Resources Branch. University research efforts have been published in the form of graduate and post-graduate theses, copies of which are at the University of Manitoba. As well, several scientific papers have been published in several journals.

THE RESEARCH BASIN APPROACH TODAY

Faced with the conditions, lack of data and the state of knowledge which existed in 1957, it is the authors' opinion that the experimental watershed approach would again be appropriate. However, a long term commitment of funding, field and research staff would be sought in the regular programming staff of a federal or provincial department to ensure commitment and continuity of the project. In addition, a project/research leader would be required who, in addition to undertaking research activities, would provide advice to the Headwater Control Committee and would enable more meaningful guidance and long-term direction for the project.

Today, with the knowledge and database from Wilson Creek; with the longer term data bases available elsewhere; and with the very great advances in hydrologic sciences over the past three decades; the authors would not recommend the experimental/research basin approach. Rather, emphasis would be placed on a multidisciplinary approach envisioning both structural and nonstructural solutions. Maximum use would be made of technology transfer from basins such as Wilson Creek, and, on regional land use plans which would be compatible with today's environmental conscientiousness and which could call for critical areas being maintained or returned to their natural state or use.

The validity of such an approach was illustrated by a number of Wilson Creek findings. For example, it was indicated that alluvial fans should be left in their natural state or rehabilitated, and, that there are no measures which can be undertaken in the headwaters which would have a significant impact on flooding problems below the escarpment. In addition, it was realized that shale erosion from the escarpment is a naturally occurring phenomenon and hence must be taken into account and accommodated in the design of hydraulic works below the escarpment.

ACKNOWLEDGEMENTS

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ASSOCIATE COMMITTEE ON HYDROLOGY
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Bad Lake Watershed: 1967 - 1986

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ABSTRACT The Bad Lake Watershed is located in the semi-arid region of Saskatchewan approximately 160 km southwest of Saskatoon. From 1967 - 1986 it was operated by the Division of Hydrology as a research facility for the training and education of students; for studies of hydrological processes and for the collection of base-line data on hydrological components important to the region. During the International Hydrological Decade it was designated as a Representative basin in the Canadian research basin program.

This paper relates the experience gained by the Division in the study. It discusses the factors influencing the decision to undertake watershed research; the project objectives; the criteria used in selecting the basin; the major problems encountered in pursuit of the program objectives; and the scientific accomplishments. The application of some of the findings to water management problems concerned with the prediction of streamflow from snowmelt and agricultural snow management practices for augmenting soil water reserves is demonstrated.

A brief summary of non-technical items a researcher may wish to consider before adopting a research basin approach to solve hydrological problems is presented.

RÉSUMÉ Le Bassin de Bad Lake est situé dans la région semi-aride de la Saskatchewan environ 160 km au sud-ouest de Saskatoon. Depuis 1967 à 1986 la Division de Recherches en Hydrologie s'est servi du bassin comme outil de formation pour les étudiants, pour mener des études sur les composantes hydrologiques et pour la collecte des données de base des éléments hydrométriques importants de la région. Durant la Décennie Hydrologique Internationale il fut désigné Bassin Représentatif a' l'intérieur du programme canadien des bassins d'étude.

Cet article relate l'expérience que la Division y a acquise. Il présente les facteurs qui ont joué dans la décision d'entreprendre de la recherche au niveau d'un bassin, les objectifs du projet, les critères utilisés dans la sélection de ce bassin, les principaux problèmes rencontrés, ainsi que les réalisations scientifiques du projet. L'article illustre aussi l'application de quelques unes des découvertes aux problèmes d'aménagement en eau reliés à la prédiction de la crue provenant de la fonte, et aux pratiques agricoles d'aménagement de la neige dans le but d'augmenter les réserves en eau du sol.

On y présente sommairement des aspects non-techniques qu'un chercheur pourrait considérer en optant pour l'utilisation d'un bassin pour l'étude de problèmes hydrologiques.

INTRODUCTION

General features

The Bad Lake Watershed is a semi-arid grassland prairie basin, approximately 264 km$_2$ in size, which is geographically-situated approximately 160 km southwest of Saskatoon at Longitude 108° 26′ W and Latitude 51° 23′N. It is a "closed" basin to surface runoff and a net discharge area for groundwater flow. The lake has a surface area of approximately 7 km^2 and except following direct runoff events the water quality is usually saline (concentrations can exceed 32,000 ppm). Occasionally it dries up in the summer due to evaporation.

The topography of the basin varies from flat to gently undulating in the south to moderately to strongly rolling in the north with altitudes ranging from 606 - 739 m. The geology comprises a glacial complex of lacustrine clays and moraine till overlying moraine shale. Lacustrine soils are dominantly of the Sceptre association of the Brown soil type with a clay content of the order of 60%; the glacial soils are of the Haverhill association with silt and clay loams being the primary textures. Except on knob and kettle topography, the drainageways in glacial-till areas are strongly-developed and well-defined. The lacustrine soils on flat topography are poorly-drained and the surface drainage area can fluctuate and vary with the magnitude of the runoff event.

Rangeland and native grass occupy approximately 20% of the gross area with the remainder, except for roads and farmsteads, under cultivation for the production of cereal grains.

The climate of the basin is semi-arid with a mean annual precipitation of 326 mm and a mean annual "class A" pan evaporation of 974 mm. On average, approximately one-third of the annual precipitation occurs as snow. The mean annual temperature is 1°C, with monthly mean temperatures ranging from -21°C in January to 18°C in July. Direct runoff is produced mainly from snowmelt and infrequently from either intense, localized short-duration rains or long-duration rains caused by frontal or cyclonic storm activity.

The Bad Lake watershed is a "Representative" watershed inasmuch as its' climate, topography and land use are "representative" of a large area of Saskatchewan. However, it probably would also be appropriate to classify it as an "Experimental" basin because the land use on 70 % of its area is under continuous change (fallow and stubble) due to farming. Also, a large part of the sub-marginal, glacial-till area in prairie grass in 1967 (20% of the basin) was broken during the late-seventies and early eighties when the price of wheat was high.

Instrumentation

To many, a research basin approach involves an application of the law of conservation of mass whereby comprehensive water balance studies are undertaken on "Representative" or "Experimental" areas whose boundaries are the surface and/or the groundwater divide. The fact that streamflow and other output information (groundwater) are requisite for water balance calculations requires a research basin. Because of the size of the Bad Lake watershed and the complex and variable nature of its' surface water and groundwater regimes it was impossible to instrument the entire basin at a level to provide reliable, spatial estimates of all hydrological components. The Division therefore opted to monitor precipitation and surface runoff on six small basins in "representative" soil, vegetative and topographic zones of the watershed. Data from these sub-units, which varied in size from approximately 10 - 60 km^2, provide hydrological information for the different landscapes and permit a rough estimate of the water balance of Bad Lake.

TABLE 1 Instrumentation at Bad Lake Watershed.

A. Climatological Station

Instrument	Frequency	Length of record
Campbell Stokes Sunshine Recorder	Daily	Jan/71 - Jun/86
RF1 Upright Kipp	Hourly	Nov/71 - Jun/86
RF2 Diffuse	"	Sep/80 - Jun/86
RF3 Inverted Kipp	"	Nov/71 - Jun/86
RF4 Net radiometer (Middleton)	"	"
Standard rain gauge	Daily	1968 - Jun/86
Tipping bucket rain gauge	Hourly	1968 - Jun/86
Fischer - Porter Storage	5 min	1968 - 1973
"	15 min	1973 - Jun/86
Nipher snow gauge	Daily	1968 - Apr/86
Class A evaporation pan (max, min water temp, 1-m wind)	Daily	1967 - Jun/86
10-m wind	Hourly	May/68 - Jun/86
Air Temperature (max, min)	Daily	Sep/67 - Jun/86
Thermohydrograph	Continuous	Sep/67 - Jun/86
Barograph	Continuous	Jul/67 - Jun/86
Soil temperature (@ 5, 10, 20, 50, 100,150 and 300 cm)	Daily	Oct/67 - Jun/86

B. Sub Watersheds

- seven small watersheds equipped with automatic stage recorders
- six with V - notch weirs, one modified broad-crested weir
- each basin instrumented with standard and recording precipitation gauges
- average period of record: 1968 - 1977

C. Lake and reservoirs

- Bad lake and two reservoirs equipped with stage recorders
- period of record: Bad lake - 1968 - 1974; reservoirs - 1968 - 1977

D. Piezometer installations

- 17 piezometers to depths of 117 m; manual records at varying time intervals: period of record: 1966 -1975

E. Research Studies

- Dense precipitation network with 41 measurement sites (32 tipping bucket, 9 Fischer Porter and 41 standard gauges) placed on a 2.7 km^2 grid; period of record: 1968 - 1975. During the summers of 1974 and 1975 soil moisture changes were monitored with a neutron gauge at 23 of the sites.
- Snow lysimeter: during 1974 and 1975 a rigorous study was undertaken on the energetics of melting prairie snowcovers using a weighing snow lysimeter. The 2.75-m diameter, circular lysimeter gave measurements of melt within 45 g. Radiation fields, 7-levels of air temperature, humidity and wind speed and soil heat fluxes were monitored.

The groundwater monitoring program consisted of five nests of piezometers, each with 2 -3 tubes installed at various depths to 117 m, which were located in each major soil zone and topographic division surrounding the lake. These measurements were to provide information on the lateral flow gradients through the Oldman formation, the major bedrock aquifer underlying the watershed, and vertical gradients through overlying bedrock shale and till formations to be used in the design of a network for the watershed.

Reconnaissance of the watershed was completed in 1965. Instrumentation was started in 1966 and the basic network was completed in 1967. Data collection began that same year and continued through 1986 (at the climatological station). Some appreciation of the extent and magnitude of the monitoring program can be obtained from the list of instrumentation (Table 1.).

NEED AND OBJECTIVES

The decision by the Division of Hydrology, which was established within the College of Engineering in 1964, to become involved in watershed research represented a natural extension of its' program. The purpose of the Division is to encourage, to co-ordinate and to supply general direction to both education and research activities of the College. To fulfil these functions, the Division considered the need to upgrade and expand its' research facilities of primary importance. Also, since members of the Division were physical scientists and engineers it was decided that the focus of the program would be directed to physical and mathematical hydrology.

The four most important considerations that influenced the decision were: (a) the lack of "high-quality" data on sufficient time and spatial scales to permit a better understanding of the physical processes and the magnitudes of components of the hydrology of the "Prairie" environment; (b) the belief that such information could not be obtained, even at exorbitant expense, from physical laboratory models because of the difficulty of simulating complex natural boundary conditions; (c) the possibility of establishing the basin within the International Hydrological Decade thereby gaining assistance (equipment and other) from governmental agencies; and (d) the interest demonstrated by federal and provincial water management agencies in the project. The primary objectives of the project were:

(1) To serve as a field demonstration laboratory and as a facility for the training of undergraduate and graduate students.

(2) To serve as a "central" facility for the collection of standard climatological, hydrometeorological, hydrometric, soil, and groundwater information in support of detailed process-oriented research studies. (It was anticipated that Bad Lake would tend to promote consolidation and coordination of research activities between University scientists and University and Government researchers.)

(3) To gain a better understanding of the hydrology of the semi-arid Prairie environment.

BASIN SELECTION

The choice of climatic and physiographic region in which to locate the watershed was relatively easy and governed to a large extent by the water-related research needs of agriculture, the mainstay industry of the prairie economy, and the need by water management agencies for data for improved hydrometeorological and engineering design. It was decided therefore, to locate in the semi-arid region of the Province because of the large land area under agricultural production of cereal grains and the low density of network observation stations. Throughout much of the region, annual potential evapotranspiration on average is about double annual precipitation, water supply and water shortages are chronic and agricultural drought not uncommon. Interestingly, if one considers collectively the number of locations where rainfall is observed by Atmospheric Environment Service, grain and fertilizer companies, water management agencies, individual producers and others the density of the regional observation network would likely be one of the highest in Canada. However little is known about the character of short-duration rainfall whose intensities approach world extremes, because of their random occurrence and their large gradients. Conversely, the hydrometric network of the province is designed primarily to monitor streamflow from perennial streams or those crossing international and provincial borders. There was, and still is, only limited quantitative information on peak flow rates and runoff volumes from ephemeral streams draining the "closed" basins which comprise the majority of "local" drainage systems of the region.

The search for a basin started in that area of the Province enclosed by a triangle having its' apex at Saskatoon and sides passing through Swift Current to the south and North Battleford to the north and extending to the Alberta border to the west. Some general features considered in the selection process were:

(1) Proximity to Saskatoon and the University,
(2) Access: all-weather roads, electrical power
(3) Drainage Basin Characteristics:

    (a) Defined drainageways for stream gauging structures.
    (b) Land use representative of dryland farming practices.
    (c) Soils and Topography: lacustrine, clay loam or heavy clay soils on flat to gently undulating topography.
    (d) Fluctuating drainage area.

(4) Interest and "potential" participation of local producers, municipality, district agriculturalists and engineers, and provincial and federal water management agencies.

After extensive review of climatological, topographic, land use and soils maps and information gathered from discussions with field and management personnel of different agencies, a short-list" of basins was drawn up for "on-site" and aerial inspection. On the basis of site visits and different assessment criteria the Bad Lake watershed was chosen. A comment on its' selection is warranted because of its' logistics, being located approximately 160 km from Saskatoon. Other basins closer to the city that were identified as potential sites were rejected because of the uncertainty about irrigation expansion around Lake Diefenbaker. In the mid 1960's various proposed schemes were under consideration and one did not wish to take the risk of instrumenting a "representative" dryland basin one year only to find it part of an irrigation project the next.

Two important features of Bad Lake that influenced its' choice were: (a) the range of soil, topographical, and vegetative characteristics representative of drainage basins in the region which were included within its' surface drainage area and (b) the interest in the project demonstrated by the local community and various water management agencies, in particular Atmospheric Environment Services (AES) and Inland Waters Branch (IWD), Environment Canada and the Engineering Branch, Prairie Farm Rehabilitation Administration (PFRA).

RESEARCH PROJECTS

A large number of studies have been undertaken within the basin or have used data collected on the watershed. Some of the topics, whose results are presented as scientific papers, conference proceedings, graduate theses and internal reports, are listed below.

(1) Precipitation

- Spatial and temporal character of Prairie rainfall
- Estimating areal snow water equivalent
- Evaluation of catch characteristics of modified nipher snow gauges
- Evaluation of catch characteristics of Fischer-Porter gauges
- Snow transport and accumulation and distribution patterns

(2) Evaporation/Evapotranspiration

- Evaporation from shallow lakes, prairie potholes, and reservoirs
- Evapotranspiration and climatic water balance
- Consumptive use of water by cereal grains under dryland farming
- Evaporation/Evapotranspiration model for non-saturated surfaces

(3) Infiltration

- Infiltration to frozen soils

(4) Soil Moisture

- Spatial variability in soil moisture
- In-situ measurements of heat and mass fluxes in unsaturated heavy clay soils during freezing and thawing

(5) Snowmelt

- Energetics of shallow prairie snowcovers
- Snowmelt runoff relationships
- Index and energy budget models for estimating snowcover runoff

(7) Groundwater

- Hydrology of prairie sloughs

(8) General

- Hydrological modelling of physical processes
- Parameter evaluation, calibration, testing and verification of "operational models".
- Instrument design, development and testing: digital field data loggers for tipping bucket gauges and profiles of soil moisture, soil temperature and hydrometeorological variables; blowing snow particle counters; weighing snow lysimeter and others.

STUMBLING BLOCKS, DIFFICULTIES

Watershed research is prone to a host of difficulties ranging from simple stream gauging problems due to refreezing of inlets at night to the more familiar problems of a lack of manpower and insufficient funding. The Bad Lake project has had its share of problems, but likely a fewer number than encountered by many research basins. It was well-supported in terms of equipment and operational assistance by a number of sources including the University, various government agencies (AES, IWD, PFRA), and the local community and by research funds received from the University and grants programs of IWD, AES, NRC, and NSERC. A major difficulty encountered, one that was not entirely unexpected but grossly underestimated, was the amount of financial, physical and human resources that had to be directed to routine field data collection-installation, servicing and maintenance of equipment; tabulation, quality control and storage of information and other similar tasks - compared to the resources used for data analyses[1]. This problem occurred despite the fact the Division employed digital data collection and storage systems in many studies early in the program. With increasing capital and salary costs coupled with fixed or decreasing levels of funding in time, the monies used for data acquisition soon reach a disproportionate level of the total program cost. Coincidentally or otherwise, under these conditions there is often less effort and attention given to review and appraisal of the data collection systems and procedures. Reappraisal on a continuing basis is essential in order to minimize or eliminate redundant and error prone information and to effect efficient planning and operational procedures.

The other significant problem was the difficulty in persuading and attracting scientists from University, Government and other sectors to locate their research within the watershed. Despite the efforts made for integration and coordination, the results were disappointing. Interdisciplinary research was accomplished only with limited success during the years the Division received monies to support hydrologic research in the form of a Development grant from the National Advisory Committee on Water Resources Research, Department of Energy Mines and Resources (Water Research Incentives Office, DOE). Through control of funding, the "potential" for coordinated studies at specified locations is substantially enhanced. In 1973/74 and 1974/75, years with the highest level of activity, 10-12 projects were either located in the area or their research directly related to the overall objectives of the watershed research program. While the success ratio in persuading university faculty to become involved with the project was small, the statistic for research personnel from both federal and provincial governmental departments, industry and other organizations was dismal. A few exceptions were small-scale studies involving intercomparisons of catch characteristics of different precipitation gages and regional monitoring of atmospheric SO^2.

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[1] Prior to its' direct involvement in Bad Lake, members of the Division of Hydrology expressed concern about the amount of time that might be required for routine data monitoring. The general opinion was that this was not a task to which a University should be heavily committed. Fortunately, the effort required for the operation of network stations was reduced significantly through participation of Environment Canada (AES and Water Survey) in such tasks as installation, repair and maintenance of equipment; extraction, tabulation, formatting, digitizing and storage of data and others.

ACCOMPLISHMENTS, IMPACT AND TECHNOLOGY TRANSFER

Accomplishments

To a large extent the Bad Lake Watershed satisfied many of the objectives and purposes for which it was intended and several accomplishments can be cited:

(1) It served as a demonstration facility for undergraduate and graduate students, visiting scientists, the community-at-large, the public and others.

(2) Approximately 20 Undergraduate, M.Sc. and Ph.D graduate theses used data from the watershed and approximately 100 publications have reported the results of research. In this regard parts of the "Handbook of Snow: principles, practices, management and use" included material from studies conducted in the basin.

(3) The research has led to a better understanding of the hydrological processes of the region. For example, the relative importance of radiative and convective fluxes to melt of a complete snowcover, sublimation losses of wind-transported snow, meltwater infiltration into completely-frozen soils, and the contribution of snowmelt to soil water reserves and agricultural production.

(4) A high-quality data base of different climatological, soil, and streamflow parameters important to the hydrology of the region has been established. Most of these data are in digital form in archives of the Atmospheric Environment Services, Water Survey Inland Waters Branch and the Division of Hydrology.

(5) The Division of Hydrology has gained National and International recognition as a group with research experiance and scientific expertise in the hydrology of a semi-arid environment, particulary in snow hydrology.

Although the basin has been officially closed for two years, it is premature to conclude that the above represent the total number of accomplishments to be expected from the program. In fact, applications of the research findings to water management problems will continue as the data are assimilated, processed and subjected to more rigorous analyses. Only recently an energy budget snowmelt model (EBSM) for open prairie environments has been developed (Gray and Landine, 1988). EBSM makes use of a net radiation model developed from measurements at the climatological station, supplemented by airborne measurements of albedo collected in a separate study; empirical relationships for convective sensible energy transfer from data collected with a snow lysimeter and soil heat flux measurements made in a study of heat and mass flux in unsaturated soil. Likewise, a snowmelt infiltration model for completely-frozen soils and an evaporation/evapotranspiration model for non-saturated surfaces have been proposed.

Impact and technology transfer

The transfer of technology to users is always a difficult task, one requiring considerable marketing and patience. As indicated above, the Divisions' approach for expediting the transfer is by means of physically-based algorithms of hydrological processes which use readily-measured parameters. These subroutines are simple, well-documented and structured and capable of being used either individually or interfaced with operational systems. In this respect, the introduction of the microcomputers into daily operational work enhance the opportunity to effect the transfer.

As a result of the research conducted in the Bad Lake Program and other studies it is believed that the understanding of hydrology of the prairie environment is at a level to allow the development of a first-generation, physically-based system for continuous monitoring and prediction of soil moisture and water supply. Such a system that uses readily-available climatic, soils, land use, and topographic information will impact on agricultural agencies concerned with planning, policy and operational aspects of crop production, drought mitigation, irrigation, pasture management and soil conservation; on water management agencies concerned with water supply, demand and management, wetlands, wildlife preservation and other groups involved with water-related activities.

During the past three years the Division of Hydrology has worked closely with the Hydrology Branch, Environment Alberta, and incorporated both an energy balance snowmelt model (Gray and Landine, 1988) and a snowmelt infiltration routine (Granger et al., 1984; Gray et al., 1986) into the U.S. Corps of Engineers Streamflow and Reservoir Regulation System (U.S. Army Corps of Engineers, 1972) that the agency uses for streamflow forecasting. Tests on Alberta and Saskatchewan watersheds with the revised system showed improved estimates in the timing and volumes of observed flow.

The established extension program serving the agricultural industry in the prairie provinces is an excellent vehicle for communicating new knowledge to agricultural representatives and local producers. Considerable effort has been expended in making the results from studies on infiltration to frozen soils available to farmers as they impact directly on the use of snow management practices for water conservation. In recent years there has been renewed interest into the use of stubble management practices (such as alternate height stubble and trap strips) for trapping snow and increasing the amount of snow water available for infiltration, thereby augmenting soil water reserves available for crops. For those unfamiliar with agricultural production on the prairies, throughout a large part the region each additional 25.4 mm of available water above a certain base level in the crop root zone at seeding will, on average, increase the yield of spring wheat by 230 - 240 kg ha^{-1}. The results of tests in completely-frozen uncracked soils demonstrate that the capacity of these soils to infiltrate meltwater is limited by the ice/water content of the shallow soil layer, 0 - 300 mm at the time of melt. Hence, there is a limit in the depth of snow that should be accumulated, which if exceeded will lead to losses to runoff and evaporation exceeding the gains by infiltration. This finding has led to experiments designed to enhance meltwater infiltration by deep tillage and subsoiling practices.

Most of the results of the research findings are available to the scientific community in the form of published papers and proceedings of conferences.

It is anticipated that the data base obtained will continue to be used by water resource managers for network and engineering design, planning, decision-making and litigation; for the development, refinement, verification and calibration of different schemes for describing prairie hydrology and processes; and for other useful purposes.

RESEARCH BASIN APPROACH

Faced with the same research needs again, namely the lack of physical data to advance the understanding and knowledge of hydrological processes, consideration would be given to a research basin approach. The choice however would be to work within an established or proposed basin in which operational and administrative support was reasonably assured over a period of not less than 3 years. There is strong question whether it is in the best interest of a University and University scientists to devote the time on administration, marketing, promotion, basic data collection and other tasks required by a successful research basin.

Based on its' experience with the Bad Lake project, a few non-technical items the Division of Hydrology would include in a checklist used to assist the decision whether to undertake watershed research are:

(1) The scientific contribution of the proposed research and the relevance and importance of the findings to local, regional, national and international needs.
(2) The potential of including the basin in an International program, such as the IHD, in which the Government of Canada has agreed to participate.
(3) The existence of a Grants program that would support "Group" or "Team" water-related research activities.
(4) A clear picture of the extent of agency involvement in respect to matters varying from direct financial support to participation in the collection, tabulation and storage of climatological, hydrometric and groundwater information.
(5) A program:

    (a) With a defined set of goals and objectives.
    (b) With modular structure that could respond to fluctuating resources with minimum disruption, and
    (c) That is reasonable and realistic in terms of existing and short-term available resources.

(6) The administrative structure responsible for basin coordination and management.
(7) The commitment of the employer to the program and type and extent of support.
(8) Mechanisms for transferring technology to users and the public.
(9) Interest and support of the local community in which the watershed is likely to be located.

It is suggested that there may be equally as strong a need for watershed research studies today as there was at the time of the IHD. This need is manifested in many areas, perhaps none greater than in education and training. In the past decade rapid advances have been made in Canada and other countries of the world in the application of mathematical modelling, computer simulation, stochastic processes, system analyses and other methodologies for solving hydrological problems. In the same period the training of hydrological processes has not advanced to the same extent. A lack of knowledge about the constraints imposed on system output by the input data and the natural environment seriously limits the use of the powerful analytical tools available today in solving practical hydrological problems.

ACKNOWLEDGEMENTS

The Bad Lake Watershed was a successful project because of the contributions by a large number of individuals, organizations and agencies dedicated to the project. To acknowledge individual contributions in detail would be a difficult and time-consuming task; one that would likely produce several inadvertent oversights. To avoid the problem the authors would like to acknowledge the contributions in a grouped manner as follows:

(1) Financial support provided by: (a) University of Saskatchewan; (b) Water Resources Grants-in-Aid Program of the Department of Energy, Mines and Resources and Water Research Subvention Programs, Inland Waters Directorate and Atmospheric Environment Services; and (c) Operating and strategic grants programs of the National Research Council and the Natural Science and Engineering Research Council.

(2) Equipment and/or engineering, technical and operational support provided by Atmospheric Environment Services; Inland Waters Directorate; Prairie Farm Rehabilitation Administration; College of Engineering, University of Saskatchewan; municipalities of Pleasant Valley and Fairview; and residents within the Bad Lake Watershed.

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The role of a small agricultural watershed to address soil and water concerns[1]

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ABSTRACT Since 1947, the Swift Current Agriculture Canada Research Station has operated a small agricultural research basin at Swift Current and Davin. These basins served to provide information on a number of different issues from an agricultural viewpoint. Initially, the watersheds were used to provide hydrometric data for the design of small agricultural water holding facilities. Later they were used to evaluate agricultural land-use practices and their impact on the quality and quantity of surface run-off. In recent years, new and improved practices such as snow management, use of soil-incorporated and non-incorporated herbicides have been evaluated using these research basins.

In addition, data derived from these watersheds have served purposes other than originally intended. For example, operational water management agencies have utilized data from these watersheds for calibration and testing of run-off models to predict surface run-off from snowmelt, evaluate evapotranspiration models, etc.

Small agricultural basins provide an opportunity to accurately assess on-farm practices that are being developed to address the soil and water concerns of today. The main difficulty in conducting this research is to experience a broad range of hydrometeorological conditions in a short period of time. Since most surface run-off occurs during the spring melt period, accurate measurement of both water quality and quantity is challenging.

RÉSUMÉ Depuis 1947, la station de recherches de Swift Current (Agriculture Canada) a géré un petit bassin de recherches agricoles à Swift Current et à Davin. Les bassins servent à fournir des renseignements sur un certain nombre de questions d'un point de vue agricole. Au début, les bassins hydrographiques servaient à fournir des données hydrométriques pour la conception de petites installations de rétention d'eau à des fins agricoles. Par la suite, elles ont servi à évaluer les méthodes agricoles d'utilisation des terres ainsi que leurs répercussions sur la qualité et sur la quantité du ruissellement de surface. Au cours de dernières années, des méthodes, à la fois nouvelles et améliorées, comme la gestion des neiges. L'emploi d'herbicides incluant ou non de la terre, ont été évaluées à l'aide de ces bassins de recherches.

De plus, les données provenant des bassins ont servi à d'autres fins que celles visées initialement. Par exemple, des organismes opérationnels de gestion des eaux ont recouru à ces données pour calibrer et pour tester des

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[1] NHRI Contribution No. 88023

modèles de ruissellement, and prédire le ruissellement de surface provenant de la fonte des neiges, évaluer des modèles d'évapotranspiration, etc.

Les petits bassins agricoles permettent d'évaluer exactement les façons culturales qu'on élabore de nos jours pour s'attaquer aux actuelles propres aux eaux et aux sols. La principale difficulté, dans le cadre de la conduite de ces recherches, est de devoir faire face à une vaste gamme de conditions hydrométéorologiques dans une prève période de temps. Comme le ruissellement de surface se produit en grande partie durant la fonte du printemps, mesurer de façon exacte et la qualité et la quantité d'eau est vraiment un défi.

INTRODUCTION

Scientists from the Swift Current Agriculture Canada Research Station have studied the semi-arid hydrology of small agricultural watersheds at Swift Current (65 ha) and Davin (1364 ha), Saskatchewan since 1947 and 1951 respectively (Nicholaichuk, 1967). The initial objective was to collect hydrologic data for the allocation of water resources and the design of small agricultural water-holding facilities. Previous studies concentrated in large prairie basins ranging in size from 4.3 million ha to 6.9 million ha (Forsaith, 1949).

The data derived from these watersheds served purposes other than originally intended. For example, the hydrologic data served to calibrate and test hydrologic model simulations. Data from the Davin Watershed were used to provide a preliminary evaluation of the revised Versatile Soil Moisture Budget (VSMB) for stream flow forecasting (Nemanishen, 1979).

With the growing environmental concern for pollution in the early 70's, dissolved nutrients in run-off water were recognized as a potential hazard to water impoundments. It has been suggested that water leaving agricultural lands may contribute significant amounts of nutrients to streams and water impoundments. The question arises as to whether run-off from agricultural lands with adequate fertility contribute to the contamination of natural waters. Utilizing the small agricultural watersheds, it was found that nutrient transport in surface run-off from fertilized, unfertilized cropped and summer fallowed plots did contain sufficient nutrients to support algal growth (Nicholaichuk & Read, 1978). Since run-off from unfertilized agricultural land contained nutrients that exceeded Saskatchewan Water Quality guidelines, the question is whether guideline limits can be met under the present system of cereal cropping in Western Canada.

The Swift Current Watershed was also used to evaluate the loss of fall-applied 2-4-D herbicide (Nicholaichuk & Grover, 1983). Although the six year average loss was 4.1% of the amount applied, the average flow-weighted mean concentration was well below the United States Environmental Protection Agency maximum permissable level of 100 g L^{-1}.

Apart from the evaluation of accepted cultural practices, the Swift Current Watershed was also used to evaluate new innovative approaches to water management. For example, the impact of snow management practices on surface run-off (Nicholaichuk, 1983). A study showed that snow management had a minimum impact on surface run-off derived from snowmelt.

In summary, small agricultural watersheds do have a definite role to play in addressing soil and water issues of today. A Canadian Senate Committee study (Sparrow, 1984) concluded that land degradation is one of the most pressing problems facing the Canadian farmer. At a recent conference 'In Search of Soil Conservation Strategies in Canada' (Anderson, 1986) one of the issues identified was as follows:

"The quality of surface and groundwaters is deteriorating due to sediment and chemical contamination from soil degradation and improper land management."

New innovative approaches to land management practices are being developed by agricultural researchers. However, it is necessary to evaluate the impact of practices from an environmental perspective. Very often the effects of soil degradation extend well beyond the farm gate. The use of watersheds makes it possible to evaluate integrated effects of improved soil and water management practices in a natural setting.

Research results from such studies have been used to establish water quality criteria. For example the Saskatchewan Water Resources Commission (1970) water quality criteria were revised to reflect more realistic levels of allowable nutrients that could be present in surface run-off.

If similar research was to be conducted again, agricultural basins of this type would be used. Small basins representative of field conditions with well defined boundaries make it possible to determine the environmental effects of cultural practices. Research basins that have a long period of hydrological records are ideal for evaluating land use and cultural practices. They provide an opportunity to evaluate innovative practices in a short period of time provided climatic conditions experienced during the study period are representative of the range of conditions that can be expected.

The main difficulty experienced in conducting this type of research is the problem of monitoring spring run-off conditions under adverse weather conditions. Heated flumes are essential to monitor flow under freeze-thaw conditions. Automated water samplers must also be protected from the environment.

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Trapping Creek and Good Spirit Lake experiences

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ABSTRACT Both the Trapping Creek and Good Spirit Lake basins were initially established for the purpose of studying the groundwater flow systems. The research objectives were subsequently expanded to evaluate the hydrological responses of the basins and to assess the water balances of the basins using hydrologic models. This paper reviews the approach taken and the problems encountered in establishing these research basins and in conducting the research studies. The usefulness and the shortcomings of the research program and results are discussed. The lessons learned from the basins and the studies have been used as the basis for a proposed basin program which is included for consideration if a new IHD program were to come along.

RESUME Les bassins du ruisseau Trapping et du lac Good Spirit ont tous deux été créés initialement pour étudier les systèmes d'écoulement souterrain. On a élargi ultérieurement les objectifs du projet de recherche afin d'évaluer le comportement sur le plan hydrologique et le bilan hydrique des bassins à l'aide du modèle hydrologique. Dans le cadre de cette communication, on se penche sur les méthodes appliquées et les problèmes survenus lors de la création des bassins de recherche et la réalisation des études connexes. On y traite également de l'utilité et des faiblesses du programme de recherche ainsi que des résultats obtenus. Les leçons tirées des travaux sur les bassins et des études connexes ont servi de base à l'élaboration d'unne programme proposé relativement aux bassins; ce dernier est inclus à des fins d'examen au cas où un nouveau programme relié à la DHI était créé.

INTRODUCTION

Both the Trapping Creek basin and the Good Spirit Lake basin (Table 1.) were established in 1965 by the then Groundwater Sub-Division of the Inland Waters Branch, Department of Energy, Mines and Resources. As originally established, the research objectives were:

(a) for the Trapping Creek basin: the study of groundwater flow systems in an area of high relief underlain by crystalline bedrock; the development of instrumentation and methodology; initially to assess underflow, and eventually to provide an annual and seasonal water balance,

(b) for the Good Spirit Lake basin: hydrogeologic study of internal drainage basin in sub-humid prairie parkland area; study of groundwater flow systems to develop improved methods of estimating the groundwater component of the hydrologic balance; to investigate the mechanism of groundwater recharge and discharge; and to arrive at a preliminary water balance for the basin.

Table 1 Description of the Trapping Creek and Good Spirit Lake Basins.

	Trapping Creek			*Good Spirit Lake*		
Location	*Southern interior plateau (Okanagan Highland) of British Columbia*			*Aspen parkland region of east-central Saskatchewan*		
Drainage area	*142 km²*			*1127 km²*		
Altitude	*900-2300 m*			*484-590 m*		
Physiography and Geography	*Mountainous with high relief underlain by crystaline bed-rock narrow mountain valley, thick surficial materials in valley bottom and thin on valley walls. Forested, logging operation.*			*Zone of rolling sandy prairie, thick surficial deposits of outwash and glacial lake sand and till overlying Upper Cretaceous sands and shales. Grain growing and rangeland grazing.*		
Climate	*Humid continental*			*Sub-humid prairie*		
Analysis Period	*1968-1972*			*1966-1973*		
Sub-basin	*Entire basin*			*Spirit Creek sub-basin*		
Annual water balance	*Ave.*	*Max.*	*Min.*	*Ave.*	*Max.*	*Min.*
Precipitation (mm)	*691*	*794*	*559*	*437*	*547*	*319*
Rain + Melt (mm)	*700*	*815*	*516*	*438*	*519*	*329*
Evapotranspiration (mm)	*377*	*409*	*348*	*405*	*461*	*301*
Runoff (observed (mm)	*337*	*445*	*179*	*21*	*49*	*5*
Runoff (simulated) (mm)	*330*	*422*	*196*	*20*	*38*	*7*
Groundwater Outflow (mm)	*0*	*0*	*0*	*2*	*2*	*1*

The desire to field test the mathematical model of the groundwater flow patterns combined with the opportunity to conduct basin studies provided by the International Hydrological Decade (IHD) during its early years, prompted the establishment of these two research basins. The basins were selected primarily because they included aspects of regional groundwater flow patterns that were then of particular interest. The Good Spirit Lake basin provided field data to test the hypothesis that the unsaturated flow processes of infiltration and evaporation are in physical and mathematical continuity with the parallel saturated flow processes of recharge and discharge. The Trapping Creek basin provided for the investigation and testing of the groundwater flow systems associated with the most prominent physiographic feature in the Okanagan Highland, a U-shaped valley underlain by crystalline bedrock.

The emphasis on the groundwater aspects of basin hydrology more or less reflects the professional interests of the original researchers. The result was a disproportionate investment in groundwater instrumentation at the expense of the kind of instrumentation required for water balances. For example, in the Trapping Creek basin, 25 piezometers and 10 water table wells were installed while only 1 recording and 2 storage precipitation gauges were set up during the course of IHD. Similar imbalance existed in the Good Spirit Lake basin. Following the completion of the groundwater studies the research effort was shifted to the testing of a generalized hydrologic model for the evaluation of basin hydrologic response and the assessment of basin water balance. Development of a snowmelt routine and a study of the evaporation pattern formed part of the overall modelling effort.

The main shortcomings of the research programs for both the Trapping Creek and Good Spirit Lake basins are discussed. This is followed by a proposal for the kind of basin program needed in the event that there were ever to be another program similar to IHD.

RESEARCH RESULTS

The process oriented research on groundwater flow patterns resulted in a wealth of published papers which are widely referenced and used for the estimation of the groundwater resources. Some examples follow:

(a) The natural basin yield of a groundwater basin can be calculated from a quantitative analysis of the flow net obtained from a digital computer solution to a numerical mathematical model of the basin (Freeze & Witherspoon, 1968). The natural basin yield is a unique property of the basin and can be considered as a conservative estimate of the safe yield, a quantity that is essential for efficient groundwater resources management.

(b) The formulation and modelling of natural groundwater recharge and discharge along with the associated unsaturated flow processes of infiltration and evaporation (Freeze, 1969; 1970) has become the theoretical basis for many other studies and investigations.

(c) The groundwater flow systems formulated and tested in the Trapping Creek basin (Lawson, 1968) can be used to provide useful estimates of baseflow in the Okanagan Highland typified by the U-shaped valley underlain by the crystalline bedrock.

The assessment of monthly and seasonly water balances for the Trapping Creek basin (Shiau, 1975) provides a useful guide to estimates of water resources in the Southern Interior region of British Columbia. The basin is considered to be representative of the runoff producing plateaus which provide water for irrigation, domestic consumption, and recreation in the semi-arid valleys of this region.

Both the Trapping Creek and Good Spirit Lake basins have been dormant since the end of the IHD. Only the hydrometric stations and precipitation gauges that are part of the national network continue in operation. Both basins are now considered to be part of the sampling network of standard observational data for water resources assessment.

The main shortcomings of the research programs for both basins were:

(a) The lack of interdisciplinary approach in establishing the research programs and in the subsequent instrumentation of the basins.

(b) The research programs for both basins were essentially "one man" shows. The success or failure of the programs depended heavily on the continuing and evolving interest of the scientist in his research topics.

(c) The lack of technical support staff resulted in a waste of the scientist's time in monitoring, collecting and processing the data.

There were a number of reasons for such shortcomings, the most important of which was the belief that much was known about hydrology. For example, those who established and worked on the Trapping Creek and Good Spirit Lake basins were well aware of gaps in their knowledge of their own speciality, hydrogeology, but were prepared, without reservation, to apply techniques from outside their speciality to estimate the evaporation and transpiration components of their water balances. This is not surprising because the documentation for those techniques provided little indication that they were based on unverified assumptions and had never been subjected to scientific testing.

The belief that much is known about hydrology prevails today. A perusal of the literature gives the impression of a vital, vigorous science making great advances in the kind of knowledge needed to solve water resource problems. Thus, there are models to simulate missing data, models to provide real-time flood forecasts, models to predict the effects of deforestation and even models to predict the hydrological effects of increasing carbon dioxide concentrations. However, a more rigorous study reveals that the scientific basis for these models is derived from the untested working hypotheses that were published in the textbooks of the 1940's and 1950's. Klemes (1986) has presented examples to demonstrate how quickly the published qualifications were forgotten and the hypotheses were accepted as self-evident truths. The result is that, 23 years after the beginning of IHD, we still know so little about hydrology that we think we know a lot. Because of this misapprehension, the financial resources and scientific skills have been directed toward the development of techniques that can provide only trivial or dubious answers, at the expense of the kind of long-term original research that is needed before worthwhile answers can be expected. Thus, we have not only failed to develop a fund of authenticated knowledge about hydrology but we have failed to develop a discipline that will permit us to do so in the future.

IF A NEW IHD-TYPE PROGRAM WERE TO COME ALONG

The initiation of an IHD-type of program with any hope of success would require a complete change of attitude on the part of all those concerned with hydrological research. This means that water planners, managers and scientists would have to admit that they know little about hydrology, treat what they have learned from university courses, textbooks and the literature with skepticism and approach the scientific and practical problems of hydrology with open minds. In the case of the planners and managers, this change would be needed before priorities could be shifted toward original basic research and away from the so-called mission oriented research which, in the context of hydrology, merely means making marginal improvements to existing techniques that have no real theoretical or empirical basis. In the case of the scientists, the change in attitude would be necessary before there could be shifts from derivative to creative thinking and from sloppy experimental techniques, which are based on the convenient assumption that unmeasurable quantities are negligible, to the kind of experimental methodology that closes all possible loopholes and eliminates the need for assumptions (see Morton, 1984; 1985 & Calder, 1985; 1986).

With a new research basin program, one would want to avoid the fragmented "everybody pick a basin" approach of the original IHD. A well-coordinated interdisciplinary program would be most desirable.

The main scientific goal of the research basin program should be to acquire the knowledge that is needed for the development of transposable and verifiable watershed models. The research should have as successive objectives:

(a) An understanding of the intricacies of the hydrologic system.
(b) The use of the understanding to formulate realistic simplifications.
(c) The development of the simplifications into mathematical forms that can utilize easily observed data.
(d) The verification of the results in many different environments.

Two types of basin are envisaged. Those that would be used as foci for plot and model studies are referred to as research basins and those whose main function would be to provide data for evaluating concepts and models are referred to as test basins. Each research basin should have a permanent corer of scientists and technical support staff. The technical nucleus should have the skills needed to monitor, collect, process, store and disseminate the data without undue delay. The scientific nucleus should include the disciplines required to disentangle cause and effect in the soil-vegetation-atmosphere system, e.g. soil physics, hydrobotany, snow physics and micrometeorology. Furthermore, surface and groundwater hydrologists would be required to develop the models that would permit the findings of the specialists to be tested on a basin scale.

With the establishment of a permanent scientific and support staff in a basin, the marginal costs of performing research on other nearby basins would be quite small. This could be worthwhile since valuable new insights could be acquired by comparing data from basins with the same macroclimate but different soils, vegetation, topography and geology. To allow for such a possibility the term research area is substituted for research basin in subsequent paragraphs.

The number of research areas to be included in the program must be based on a realistic assessment of the resources that can be committed over a period of at least twenty years. The selection of individual research areas should be based on regional representation, a demonstrated tradition of interdisciplinary research in the local hydrological community, the homogeneity of the basins and, to a lesser extent, the heterogeneity of the region in which they are located.

The test basins would exist primarily to evaluate the modify models that have been developed in the research areas. These test basins should be operated continuously with a common minimum standard of instrumentation and with an efficient procedure for monitoring, collecting, processing and disseminating the data. Furthermore, they should be located in many different environments and, ideally, become parts of the hydrometric and meteorological data collection networks.

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A major economic development - the result of the Quill Lake IHD Project

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ABSTRACT The Big Quill Lake basin is one of the largest internal drainage basins in Canada, covering 2500 km^2. The brine in the lake contains about nine million metric tonnes of magnesium sulphate and about seven million tonnes of sodium sulphate. These salts, at the current prices, would have a gross sales value of half a billion dollars. A plant has been built to extract these minerals over the next 20 years. This plant was designed based upon the results of the International Hydrological Decade study.

The Big Quill Lake study started in 1966. The water balance of this large, shallow lake was investigated in sufficient detail to make sound conclusions and to enable future planning of the development of its resources such as recovery of salts in the brine, and use of fresh water for municipal, agricultural, wildlife and recreational purposes.

Basic data have been obtained on the volume of water entering the lake from spring runoff, ground water inflow and precipitation. Estimates of these parameters have been made from 1922 to 1982 to assist in predicting future lake conditions. The salts in the lake have been dissolved from surface and sub-surface soils and tills by water moving towards the lake. The water which arrives in the lake is then concentrated by evaporation. Analysis of lake bottom sediment cores has shown that the ratio between slats has been constant for 10,000 years. The 12 year IHD study has produced conclusions on which the future potential of the lake should be based. Statistically it is improbably that man could force a major change in the water and salt balance of the lake. The water budget of the lake is controlled by basin characteristics (such as topography and basin shape) and not directly from climatic input (such as precipitation or evaporation). The salt balance if therefore the end result and is the best estimator of the basin's history.

For example, if man wished to hold the lake at its present condition, the runoff would have to decrease by 40% and this water injected into the groundwater regime to increase the groundwater by 300%.

RÉSUMÉ Le bassin de Big Quill Lake couvre 2500 km^2 et est un des plus grands bassins de drainage fermé du Canada. L'eau du lac contient environ 9 millions de tonnes métriques de sulphate de magnésium, et sept millions de tonnes métriques de sulphate de sodium. Ces sels, aux prix courants, auraient une valeur brute de revente de un demi-milliard de dollards. Une usine est maintenant en place pour extraire ces sels sur une période de 20 ans. La conception de cette usine repose sur les résultats d'une étude de la Décennie Hydrologique Internationale.

L'étude de Big Quill Lake a débuté en 1966. Le bilan hydrique de ce grand lac peu profond a été étudié assez en détail pour tirer des conclusions bien fondées et permettre la planification, alors à venir, du développement de ses ressources, incluant la récupération des sels en solution, et l'utilisation de l'eau douce pour des fins municipales, agricoles, municipales et fauniques.

On a obtenu des données de base sur les eaux de charge du lac provenant de l'écoulement de fonte, de la nappe, et de la précipitation. Ces paramètres ont été estimés de 1922 à 1982 de façon à faciliter la prédiction des conditions à venir. Les sels dans le lac sont mis en solution dans les sols et tills de surface et en profondeur par l'eau s'écoulant vers le lac. La solution du lac se concentre ensuite par évaporation. L'analyse de carottes des sédiments sous le lac a révélé que le rapport de la concentration des sels a été constant depuis les derniers 10,000 ans. L'étude de 12 ans de la DHI a produit des conclusions qui devaient servir de base pour l'estimation du potentiel futur du lac. Il est statistiquement peu probable que les activités humaines puissent altérer fortement le bilan de l'eau et des sels du lac. Le bilan hydrique est contrôlé par les caractéristiques du bassin (topographie et morphologie), et non pas directement par les facteurs climatiques (tels que précipitation et évaporation). Le bilan des sels est la résultante de ces influences et est le meilleur estimateur de l'historique du bassin.

Si, par exemple, on désirait maintenir le lac dans sa condition actuelle, il faudrait intercepter 40% de l'écoulement de surface et l'injecteur dans la nappe phréatique afin d'augmenter cette dernière de 300%.

INTRODUCTION

The Big Quill Lake basin is one of the largest internal drainage basins in Canada. The basin covers 2500 km^2. The brine in Big Quill Lake contains about nine million metric tonnes of magnesium sulphate and about seven million tonnes of sodium sulphate. The Big Quill Lake IHD study started in 1966 to determine whether economic use of these salts could be made. The objective of this study was to investigate the water balance of this large, shallow lake in sufficient detail to make sound conclusions and to enable future planning of the development of its resources such as recovery of slats in the brine, and use of fresh water for municipal, agricultural, wildlife and recreational purposes.

The study obtained basic data on the volume of water entering the lake from spring runoff, ground water inflow and precipitation. Estimates of these parameters were made from 1922 to 1982 to assist in predicting future lake conditions. The study found that the salts in the lake have been dissolved from surface and sub-surface soils and tills by water moving towards the lake. The water including the dissolved slats which arrives in the lake is then concentrated by evaporation. Analysis of lake bottom sediment cores showed that the ratio between slats have been constant for 10,000 years. The 12 year IHD study and subsequent Environmental Impact Assessment produced conclusions on which the future potential of the lake should be based. The water budget of the lake is controlled by basin characteristics (such as topography and basin shape) and not directly from climatic input (such as precipitation or evaporation).

WHY A BASIN RESEARCH APPROACH?

Big Quill Lake basin is an internal drainage basin. It can be distinguished from an open basin by its topography and hydrology. All points in the internal basin drain into a lake or series of lakes below the elevation of the boundary or perimeter of that basin. An internal basin is endorheic. Therefore if the surface water balance parameters can be determined accurately, the groundwater component will be the residual.

Hydrometeorological phenomena are dynamic so their comprehensive and predictive nature are both difficult and challenging. They contain cyclic components ranging from diurnal to climatic trends. Predicting the magnitude and occurrence intervals was the aim of the IHD study. The only method which could provide the full range answers, from diurnal to climatic, was a basin study.

From historical records and studies dating back to 1992, it was known that large fluctuations have occurred over time. Now, with a depth of only 3 metres and covering an areas of 250 km^2, this lake can vary up to 25% of its depth in a single season. In consequence, an imbalance between components of the water budget causes relatively large fluctuations in water level in proportion to its depth. Thus the continued existence of the lake appears to be dependent upon a delicate balance between these components. Two possible explanations of the maintenance of this balance were offered. One is that the lake is relatively independent of groundwater discharge, although this is a small persistent flow, and that its existence depends upon much more on the balance between larger meteorological parameters including surface runoff. This explanation indicates a sensitive dependence upon climatic factors from year to year. The alternative explanation is that the groundwater component is more directly related to lake level changes from month to month and that if there is a change of lake level it reflects a change of pressure in the connecting aquifer system more than a change of balance between climatic factors during one particular year.

In either case the mechanism is the same. The difference lies in the response time of groundwater flowing into the lake. This inflow depends on the permeability of the material where recharge is taking place to the aquifer and the bed where discharge to the lake is occurring. Since the lake does not have an outflow, the difference between cumulative effects of surface inflow, precipitation and evaporation must give a measure of groundwater discharge. An experimental program was set-up to obtain estimates of the parameters. A large quantity of data was collected in the course of this study and stored on computer tape on a weekly time scale.

CURRENT ACTIVITY

The brine in the lake contains about nine million metric tonnes of magnesium sulphate and about seven million tonnes of sodium sulphate. A plant has been built to extract these minerals over the next 20 years. This plant was designed based upon the results of the International Hydrological Decade study. The plant uses a ion exchange between potash (KCl) and Sodium sulphate ($Na\ SO_4$) to form Potassium sulphate (KSO_4) with a by-product of sodium chloride (NaCl). The current plant produces 10 $t\ d^{-1}$. This plant will soon be enlarged to 100 $t\ d^{-1}$. No other activity is currently being undertaken although data from this study are used as background for other studies to be mentioned later.

ACCOMPLISHMENTS AND DISAPPOINTMENTS

The project provided 3 models: rain, climate and salt. Of these the salt and climate models have been adopted for the planning of the plant. The data from this IHD study have been used as a basis for two MSc theses, five refereed journal articles and numerous symposium articles. These are listed in the references. A citation was also given by International Electrical and Electronic Engineers (IEEE).

Early on in the project, it was recognized that the groundwater component was not going to be accurately determined and that not enough funding could be found to cover an adequate exploration program. This factor proved

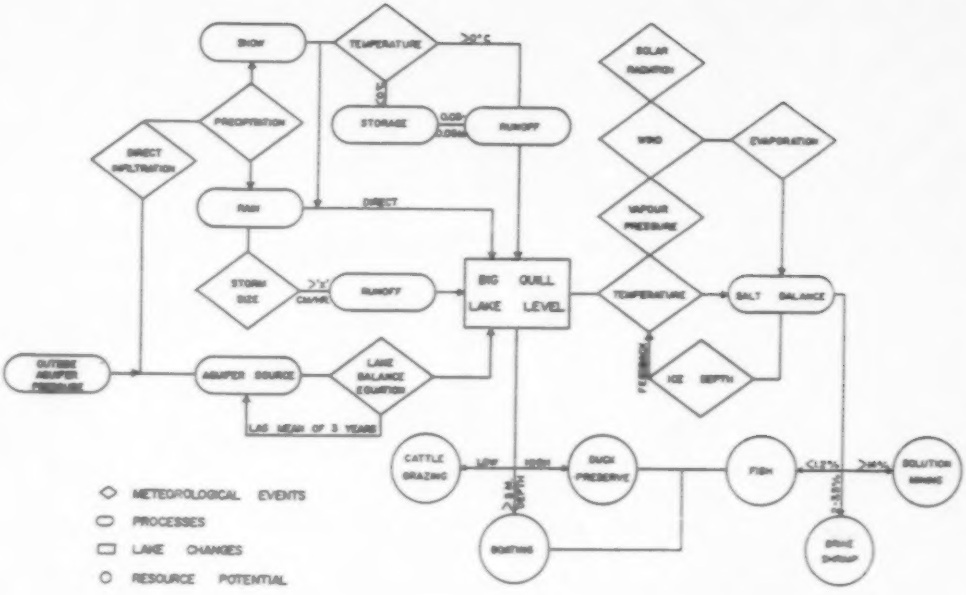
SNOW
TEMPERATURE
>0°C
<0°C
PRECIPITATION
STORAGE
RUNOFF
DIRECT INFILTRATION
RAIN
DIRECT
STORM SIZE
>'X' CM/HR
RUNOFF
BIG QUILL LAKE LEVEL
OUTSIDE AQUIFER PRESSURE
AQUIFER SOURCE
LAKE BALANCE EQUATION
LAG MEAN OF 3 YEARS
SOLAR RADIATION
WIND
EVAPORATION
VAPOUR PRESSURE
TEMPERATURE
SALT BALANCE
FEEDBACK
ICE DEPTH
CATTLE GRAZING
LOW
HIGH
DUCK PRESERVE
BOATING
FISH
<12%
SOLUTION MINING
BRINE SHRIMP
◇ METEOROLOGICAL EVENTS
⬭ PROCESSES
▭ LAKE CHANGES
○ RESOURCE POTENTIAL

FIG.1 Conceptual balance model.

to be the main failing of the project. The climatic model also lacked the wizardry of the modern mathematical models of today such as Global Circulation Model (GCM). Therefore, the residual methods used have many holes by today's standards.

CONCLUSION

The hydrological model envisaged for this basin is provided in Fig.1. The hydrological model is composed of a water balance model equation. The water balance drives the salt balance of the lake. The equations were derived and calibrated for this conceptual model from the research basin study. The major components, which were studies, were precipitation (snow and rain), aquifer storage, lake level, water budgets (winter, summer and annual), and evaporation. Precipitation was found to be the most important predictive parameter.

The study produced seven conclusions:

(1) Statistically it is improbably that man could force a major change in the water or salt balance of the lake;

(2) It is estimated that man will increase the area drained by the lake by 15% by artificial means but will also add another 10% kin storage in channels. In 50 years, this change in basin conditions will increase the lake level by 0.31 m;

(3) The lake is controlled by basin characteristics and not directly by the climatic input;

(4) The salt balance is therefore the end result and is the best estimator of the basin's history. For example, if the lake is to be controlled at its present level, the runoff would have to be decreased by 40% and this water injected into the groundwater to increase the ground water contribution by 300%;

(5) The annual lake level fluctuation has been calculated to be composed of 10% winter precipitation, 53% net evaporation, 24% spring runoff, and 13% groundwater;

(6) Over the last 10,000 years, the average ratio between these parameters has remained the same;

(7) Annual precipitation falling on the lake has been shown to be divided into the following apportionments: 24% runoff, 13% groundwater, 45% evaporation, and 18% lake level change.

Due to the expense, $1.5 million (in 1975 dollars), it is not probable that such a study could be attempted today. In another 5-10 years, remote sensing will make this type of study a fairly routine and cheap project. Aerial precipitation (both rain and snow), aerial snow water equivalent, shallow aerial groundwater, aerial lake evaporation and aerial evapotranspiration will all be available from satellite.

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The Tri-creeks watershed research study (1965-1986) Hinton, Alberta

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ABSTRACT In 1965 the Alberta Department of Lands and Forests initiated the Tri- Creeks Watershed Research Study south east of Hinton, Alberta. The purpose of the study was to determine the impact of timber harvesting on fish populations in foothills streams, and, in so doing, evaluate the ground rules and guidelines used to control timber harvesting. A multi-disciplinary approach was chosen to evaluate the impacts of changes in streamflow, ground water movement, climate, vegetation, basin geology, and water chemistry on the population dynamics of fish (primarily rainbow trout) and macroinvertebrates. The study was unsuccessful in relating cause and effect primarily because of the lack of a good overall research design and control. The results of this study will have little impact on altering present forest harvesting practices. However, the fisheries knowledge gained from Tri-Creeks is expected to directly affect fisheries management in other foothills streams.

RÉSUMÉ En 1965, le "Department of Lands and Forests" démarrait le projet de recherche du bassin de Tri-Creeks, au sud-est de Hinton, Alberta. Le but de l'étude était de déterminer l'impact de l'exploitation forestière sur les populations de poissons dans les ruisseaux des contreforts des Rocheuses, et, par le fait même, d'évaluer les règlements et lignes directrices qui servent à régir l'exploitation. L'approche multi-disciplinaire choisie avait pour but d'étudier l'impact des différences de débits, d'écoulement souterrain, de climat, de végétation, de géologie des bassins et de chimie de l'eau sur la dynamique des populations de poissons (surtout la truite arc-en-ciel) et de macro-invertébrés. L'étude n'a pas réussi à établir des liens de causalité à cause de manques dans sa conception et son suivi. Les résultats de cette étude n'auront que peu d'impact sur les pratiques forestières. Cependant, l'information halieutique tirée de l'étude de Tri-Creeks devrait affecter directement la gestion de la pêche dans les autres cours d'eau des contreforts.

INTRODUCTION

In February, 1960 the Department of Lands and Forests of the Alberta Government sponsored a natural resources conference in Edmonton. The conference focused on large scale pulpwood harvesting and its possible effects on water flow regimes and water quality of Eastern Slope streams. Out of the conference came the recommendation for an Alberta study in the foothills which would address this concern.

In January, 1965 the United Nations Educational, Scientific and Cultural Organization (UNESCO), sponsored the International Hydrologic Decade (IHD). The purpose of the IHD was to accelerate the study of water resources and their regimen with a view to their rational management. Under the auspices of the IHD and as part of the Alberta Watershed Research Program, the Tri-Creeks Watershed Study was initiated in 1965 by the Department of Lands and Forests (Fish and Wildlife Division and the Alberta Forest Service). The purpose of the study was to evaluate the effects of pulpwood harvesting on the physical, chemical and biotic qualities of western Alberta trout streams. The results of this study were to be used to evaluate the ground rules and guidelines controlling forest cutting practices on the foothills.

The objectives for the study were based on two conditions:

(1) the primary focus was on the aquatic ecosystem, and in particular, the fish populations; and,

(2) normal logging operations under the current ground rules were to be followed, the exception being that stream side buffers were to be removed in one of the basins.

The study's primary objectives were:

(1) to determine the effects of clearcutting on the survival, growth and reproduction of fish and aquatic invertebrate populations;

(2) to determine the effects of stream side timber removal upon water temperature, streamflow and suspended sediment;

(3) to determine the effects of clearcutting upon streamflow regime and the duration and magnitude of peak flows;

(4) to determine the effects of road construction and clearcutting upon suspended sediment concentrations and stream channel siltation;

(5) to determine the effects of clearcutting upon the chemical quality of streams.

The intent of objectives 2 - 5 were to help explain any possible changes that may have occurred in objective 1.

RESEARCH APPROACH

No documentation seems to exist as to why the research basin approach was chosen for the Tri-Creeks study. However, the following factors were undoubtedly influential in using this approach:

(1) the 1960 conference in Edmonton had recommended such a study be carried out in the foothills;

(2) the introduction of the International Hydrologic Decade was encouraging such a research basin;

(3) during the 1960's other basin research studies were being set up in Alberta;

(4) the initiator of the project, Gorden Hagen of the Fish and Wildlife Division, was from the United States where basin research projects were

in vogue. Being a strong promoter, Mr. Hagen was able to build in the climate already set and get the study off the ground.

STUDY LOCATION

The most important site selection factors were:

(1) access - a forestry road ran the full length of the largest basin and an old oil industry road accessed the headwater regions of the other two basins;

(2) timber - for the most part the timber was virgin and the area undisturbed, although some scattered logging occurred in the early 1950's;

(3) operations - the basins were for the most part in an area being managed by a large company, which made long range planning easier;

(4) location - the streams are true foothills streams, important as fisheries for salmonid fish such as rainbow trout; and,

(5) uniformity - it was felt the basins were both geologically and climatically similar enough to ensure good results.

RESEARCH DESIGN AND CONTENT

No formal overall project design was put in place until 1984, when the logging phase was already completed. Up until that time, participating agencies tended to develop their respective programs in isolation of one another, bound only by the broad framework of the study objectives.

The research design developed in 1984 is outlined below in Table 1. This project design had no value in directing activities in the pre-logging and logging phases of the study, but it had some utility in directing post-harvesting research activities. It was also useful in providing a framework for data analysis and report writing.

LEARNING EXPERIENCES

A number of learning experiences from the Tri-Creeks study are outlined below.

(1) Good data/results require a good project design with clearly articulated and attainable objectives.

One of the results of not having a formal project design being put in place until after the pre-harvesting and harvesting phases was expensive information being gathered and not used, while information that should have been gathered was not.

(2) There is no substitute for good quality control.

Quality control means:

(a) adopting and maintaining standard procedures for data collection, handling and analysis; and,

Table 1. Research projects conducted in Tri-Creeks

STUDY COMPONENT	PROJECTS	DESCRIPTION
Forestry	Harvesting and Silviculture	- Document harvesting and silviculture treatments. - Compare treatments with other watersheds within the Champion Forest Management Area.
	Watershed Management	- Document watershed management practices conducted in the study area. - Identify problem areas and provide recommendations for corrective measures.
	Site Classification	- Provide an ecosystem classification for the study area.
Climatology	Climate	- Characterize macro climate (relative humidity, air temperature and precipitation).
	Hydrometeorology	- Characterize storm frequencies and intensities. - Compare precipitation regimes with AES stations in the vicinity of Tri-Creeks.
	Snow Regime	- Describe snow accumulation and distribution in a large clear-cut and adjacent forest.
Water Resources	Hydrologic Regime	- Describe seasonal streamflow during the ice-free period.
	Hydrochemical Regime	- Characterize surface water quality.
	Sediment Regime	- Used to evaluate the effects of road construction, harvesting and buffer strips.
	Surface Thermal Regime	- Characterize surface water thermal regime of watersheds with treed buffer strips and following removal of buffer strips.
	Channel Regime	- Describe evolution of pool volumes, bed materials, channel stability and critical discharges to move bedload during incubation periods of fish eggs.
Geosciences	Soils and Erosion	- Describe soils and soil erodibility.
	Hydrogeologic Regime	- Characterize ground water levels, chemistry and temperature in relation to surface water.
Aquatic Ecology	Population Dynamics of Salmonid Fish	- Characterize migratory movement, spawning habitat, fecundity, interstitial chemistry, water temperature, survivorship, age and growth.
	Macroinvertebrate Ecology	- Evaluation of the effects of sediment input from a point source on macroinvertebrate species abundance, biomass, diversity, and richness.

(b) ensuring those procedures are being properly carried out and the data is good.

Throughout most of the study a rigid quality control program was not in place. The result was that water chemistry information being poorly collected and later discarded, leaving a gap in the data set. Also, methods for collecting and analyzing data changed over time, making the comparison of some data sets, e.g. streamflow and suspended sediment information, between the pre-harvesting and post-harvesting phases difficult.

(3) A commitment to a minimum period of time for each of the pre- and post-harvest evaluation period is essential to ensure the integrity of the study.

(a) Harvesting was initially scheduled to start in 1977 but was later moved up to 1979. It then took two additional years (five years instead of three) to harvest the two basins due to poor weather conditions and an economic slow down. Since no additional time was given to the post-harvest evaluation period to compensate for the years lost earlier in the study, the Wampus and Deerlick basins had post-harvest evaluation periods of only three and two years, respectively.

(b) The termination of the study at Tri-Creeks leaves two important questions unanswered:

- what is the rate of recovery of the watershed in terms of water quality and quantity? and
- what will happen after the second cut takes place?

The integrity of the study has been justifiably questioned because of the short post-harvest evaluation period and the lack of vision for what might be expected beyond the first cut.

(4) A solid project management structure is vital.

It was not until the last three years of the study that a proper management structure was put in place. What would have been beneficial to Tri-Creeks would have been the following:

(a) central coordination under one lead agency;

(b) a project team organization with a technical advisory committee;

(c) an experienced, professional project manager with the necessary support staff; and,

(d) a long term allocation and commitment of resources and land to the project by industry and government.

ACCOMPLISHMENTS

(1) the study provided an opportunity to develop and evaluate sampling techniques for such things as point source sampling, which have been incorporated into both government and industry monitoring programs;

(2) the study provided valuable information on the dynamics of fish populations in eastern slope streams, which the staff from Alberta Fish and Wildlife have found useful in developing fish management strategies for the eastern slopes streams;

(3) the Tri-Creeks study produced three Masters of Science thesis and valuable summer work experience for university and technical students; and,

(4) given the constraints on the data collected the study generally confirmed the results found elsewhere regarding the affects of timber harvesting on stream flow, suspended sediment levels and stream temperature when stream side vegetation is removed.

EXPECTED IMPACT OF THE STUDY OUTSIDE TRI-CREEKS

The inability of the study to show a cause/effect relationship between changes in the aquatic community and changes in individual parameters such as stream flow, suspended sediment levels, water temperature changes or water quality greatly reduces the utility of the information elsewhere.

Hydrologically, the study will not provide anything new, but simply confirms what is already known. For example:

(1) water yield increases with removal of vegetation;

(2) during logging operations, road and stream crossings provide most of the sediment to the stream;

(3) removal of stream side vegetation increases water temperature; and,

(4) removal of timber under normal logging operations appears to have little effect on overall water quality in terms of nutrient loading and leaching of minerals from the watershed.

AVAILABILITY AND USE OF THE INFORMATION

Pending approval by the Assistant Deputy Minister of the Alberta Forest Service, the research findings will become available to the public and the research community.

Once released the Tri-Creeks study results can be expected to find their greatest utility in the following manner.

(1) The Alberta Forest Service, serving as the watershed manager and responsible for the proper delivery of water from Alberta's forested area to the stream channel, will, where possible, use the study's results to revise any ground rules found wanting.

(2) Alberta Fish and Wildlife, responsible for the management of fisheries resources, has already found the fisheries information useful in understanding fish population dynamics in foothill/mountain streams and expects to use this information in managing those streams.

(3) Alberta Environment, serving as the province's principal water manager (distributor of water), is interested in continuing streamflow measurements at the mouths of the three streams. This, in a limited way, could help monitor the recovery period and, possibly, the effects of the second cut. However, this monitoring should not be compared with the monitoring that would be carried out under a proper research program.

AN EVALUATION OF THE BASIN APPROACH

If the question of the effect of logging on the biotic community was posed again, the research basin approach would still be the primary consideration. No models, to our knowledge, exist that predict with any confidence, what the biotic community composition and dynamics of any particular stream will be given a specific activity/change on the watershed.

In terms of doing things differently, two areas must be considered: leadership and study design.

(1) From the perspective of leadership, the primary concerns would be to ensure that:

    (a) strong and competent research leadership is in place to provide direction and project control throughout the whole study; and,

    (b) management has made a strong commitment to the intent of the study, evidenced by support in terms of resources, land, and whatever else it might take to ensure successful completion of the study.

If strong leadership had been present in both these areas, many of the problems experienced in Tri-Creeks would have been minimized.

(2) From the perspective of study design, careful thought must be given to the questions being asked and the program(s) required to answer those questions. In Tri-Creeks an intense fisheries monitoring program was developed, particularly in relation to fish population dynamics. Unfortunately, the same level of monitoring intensity was not followed when looking at climate, hydrology, water chemistry and soil erosion. Because of this, the study was not able to readily determine any cause/effects relationships between timber harvesting and changes in fisheries populations. In turn the study had limited success in meeting its objectives.

If another Tri-Creeks type situation arose, much more intensive monitoring programs, based on a well thought out program design, would be recommended with the intent of determining cause/effect relationships and defining the processes used to drive those relationships.

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Cache Percotte watershed study, Hinton, Alberta

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ABSTRACT This project was established as an adjunct to the operations of the Forest Technology School. The major purposes were for education and demonstration to illustrate techniques in forest hydrology and watershed management. The study objective was to determine streamflow characteristics and water balance before, during and after forest harvesting. Technical difficulties in developing the project, particularly in streamflow gauging are described. Data have been collected but not compiled. The area has been of value in teaching and demonstration.

RÉSUMÉ Ce projet a été mis sur pied comme complément aux opérations du "Forest Technology School". L'emphase a été mis sur l'éducation et la démonstration de techniques d'hydrologie forestière et d'aménagement de bassins hydrographiques. Le but du projet de recherche était de déterminer le bilan hydrique et les caractéristiques du débit avant et après la coupe. Les difficultés techniques rencontrées, particulièrement dans le jaugeage des débits, sont décrites. Les données récoltées n'ont pas encore été réduites. Le bassin a été utile comme outil pédagogique et aire de démonstration.

INTRODUCTION

The Cache Percotte Watershed study encompasses the headwaters of two drainage basins: Cache Percotte (679 ha) and Whiskeyjack (301 ha), a tributary of Hardisty Creek in the Hinton area (53° 26'N 117° 32'W). Both flow northerly into the Athabasca River, part of the Mackenzie River system. Elevations on the basins range from 1150-1400 m on Cache Percotte, and 1185-1430 m on Whiskeyjack (Fig.1). The basins are forested with typical Sub-alpine (Rowe, 1972) species, predominantly white spruce (*Picea glauca* var. *albertiana*), black spruce (*Picea mariana*), lodgepole pine (*Pinus contorta* var. *latifolia*) and white and balsam poplar (*Populus tremuloides* and *P. balsamifera*). The stands are largely of fire origin. The basins were virtually undisturbed by logging although a few stands had been subject to partial cutting for sawlogs and railway ties in the 1930s and 1940s.

When the Forest Technology School, a technical forestry training institution, was established in Hinton in 1960, arrangements were quickly made to delineate a school forest to serve as a base for training activities, demonstrations and longer-term studies. The area was selected to include the headwaters of these two small drainages. The basin configuration reflected both the historic influence of watershed concerns along the east slopes of the Rocky Mountains beginning from the Forest Reserves Act of 1911, and the subsequent definition of forest management units largely based on heights of land. This specific project was first outlined in 1963, and work started on

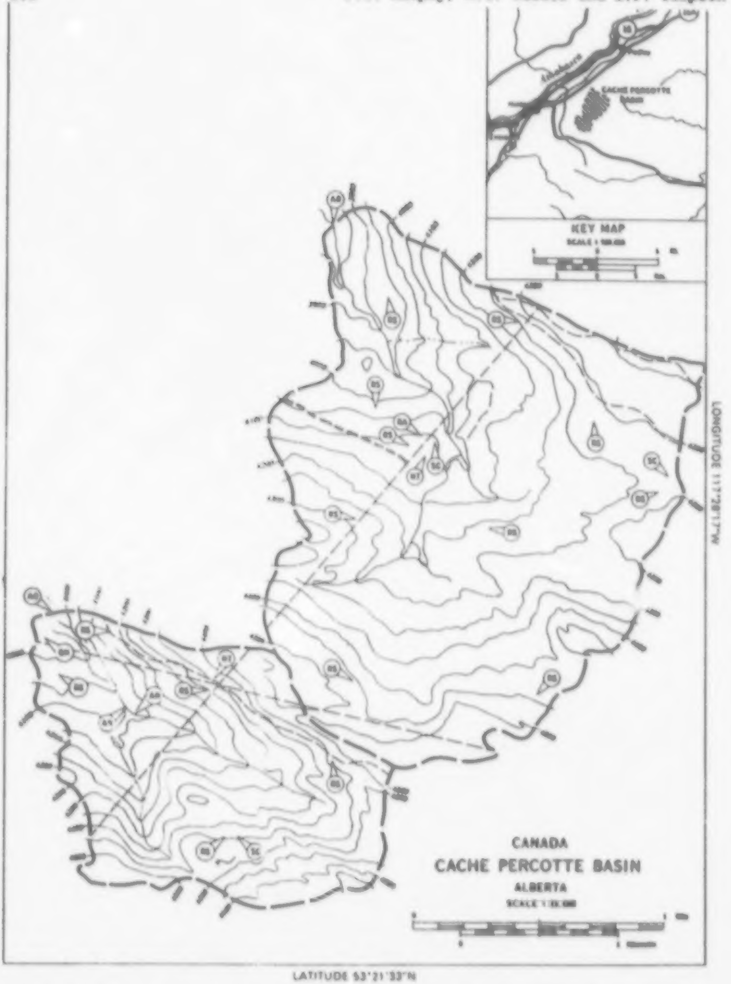
Athabasca
CACHE PERCOTTE BASIN
KEY MAP
LONGITUDE 117°28'17"W
CANADA
CACHE PERCOTTE BASIN
ALBERTA
LATITUDE 53°21'33"N

FIG.1 Location of Cache Percotte watershed study basins, Hinton, Alberta.

rain gauge and flume installations in 1964. Streamflow measurements commenced in the spring of 1965. The project was recognized in 1965 as an International Hydrologic Decade study (IWB-EB-4-Alberta-3).

NATURE OF THE STUDY

The project was initiated and directed by staff of the Forest Technology School, operated by the Training Branch of the Alberta Forest Service. It was intended to be run by school staff as an adjunct to training operations. Technical advice and assistance was obtained from nine agencies.

Streamflow measuring devices were sited and designed by staff of the Water Resources Branch of Environment Canada. Because of anticipated movement of streambed gravels, flumes were employed as the major control devices to minimize maintenance problems. An H-type flume was placed on Whiskeyjack Creek. It measured 3.6 m in length, 0.9 m deep, and width of 1.4 m. It functioned well, but the original metal flume was replaced by a larger plywood-style installation in 1970 after peak flows in August, 1969 exceeded the capacity of the original. A trapezoidal flume was installed on Cache Percotte Creek. It was constructed on concrete around a metal frame. The structure measured 2.7 m in length, 0.9 m deep, and with a 4.1 m spread at the top of the sloping walls. Both were placed on concrete cutoff walls dug into impermeable material. The Water Resources division of Alberta department of Agriculture provided Stevens A-35 waterlevel recorders. V-notch weirs on plywood cutoff walls were intended for gauging tributary flows.

The Atmospheric Environment Service of Environment Canada advised on placement of weather instruments. A network of fifteen rain gauges along with a central weather station, three Sacramento precipitation storage gauges and three snow courses was established.

Three divisions of the Research Council of Alberta made significant contributions. Two groundwater wells and piezometer clusters were located and installed by the Groundwater Division, a surficial geology survey was completed by the Geological Surveys Division, and the Soils Surveys Division conducted a soil survey. The Water Resources Division of Alberta Environment provided the Stevens A-35 water level recorders. Sediment samples were analyzed, and compilation of the hydrological data were undertaken by the Water Resources Branch of Environment Canada.

Access was seriously limiting at the start, but roads were gradually provided through the Alberta Forest Service Construction Branch, and trails were constructed by AFS Junior Forest Ranger crews to enhance servicing of the project and use of the area by students. Contour maps were also provided through the Alberta Forest Service. Important technical assistance and advice were provided by staff of the Canadian Forestry Service and of the former Eastern Rockies Forest Conservation Board.

Maintenance of the project and data collection were done by staff of the Forest Technology School.

REVIEW AND EVALUATION

Objectives

The purpose of the Cache Percotte Forest was to serve as a training and demonstration area for programs of the Forest Technology School. The aim has been to manage the area on an integrated forest resource use basis. The forests were to be sustained-yield basis, with the plan modified as necessary to meet educational needs. Anticipating an eventual harvest of the forest on the two basins, the objectives of the study were to:

(a) calibrate the basins to determine the water balance in their undisturbed conditions,
(b) observe the effect on the precipitation-runoff characteristics resulting from systematic harvesting of the timber stands, and
(c) serve as a demonstration area in the techniques of forest hydrology, watershed management and related studies.

Research basin approach

The basin approach was selected for two main reasons: the typical watershed approach to land management units mentioned previously, and the easily-grasped relationship between streamflow and drainage within basins from an educational standpoint. These particular basins were selected in connection with setting up the school forest.

Topics studied

The study emphasis was on the relationship between precipitation and stream flow to establish a benchmark relationship in an undisturbed situation. It was expected that this would be a long-term study to try to determine the changes which might result from later orderly harvesting on the basins. Related studies included monitoring of suspended sediments and groundwater fluctuations.

Difficulties encountered

Ice-massing on the stream-gauging structures In light of the low winter flows and the use of flumes rather than weirs, it was not anticipated that streamflow readings could be maintained during the period of freeze-up. However, we did not anticipate the massive build-up of ice over the flumes which effectively precluded measuring of spring snowmelt from the basins except in a couple of notable instances. A variety of propane-fuelled heaters was employed to try to keep the control notches and wells clear of ice so the flumes could be activated when the thaw began. However, none proved effective during the coldest weather, and all posed great problems in servicing.

A second approach was construction of bypass channels around the flumes through which winter flows could be diverted. This worked well until the diversion channels themselves became glaciated forcing a re-routing of the flows through the flumes again, only delaying the onset of ice massing over the control structures.

No solution to this problem was found. At the approach of breakup, ice would be manually chiselled out of the flumes. However, ice masses below the flume would commonly back up the runoff flows rendering the flume recordings valueless.

Trapezoidal flume design The trapezoidal flume functioned well in handling the problem of moving gravel in the stream bed. Unfortunately, the underground pipes connecting the flume to the stilling well remained frozen until long after the snow runoff had passed, further delaying the start of spring readings.

Although the cutoff wall was dug to impermeable soil, the surrounding material was unable to support the weight of the heavy concrete flume structure which had been poured in place. Under those difficult conditions it later shifted in 1975. Attempts were made to recalibrate the flume, but the structure had been rendered unserviceable and it was abandoned after the 1977 season. On reflection it would have been preferable to have used a larger rectangular flume similar in design to that on the Whiskeyjack basin which would have been both lighter, and easier to have replaced if necessary.

V-notch weirs The seemingly-simple solution to monitoring summer flows of tributary streams by the use of V-notch weirs on plywood cutoff walls proved to be unworkable. It was not possible to maintain a watertight seal, and water invariably found its way below or around the cutoff wall. During times of high flow, the structures inevitably washed out. The cutoff walls were extended and deepened to the extent practicable for hand labour, and sealing was attempted with bentonite but without success.

When the metal flume on Whiskeyjack Creek was replaced, it was reinstalled on the north fork of Cache Percotte Creek in 1971. Poured concrete cutoff walls and use of a flume without creating an impoundment seemed to be the best workable structure under those conditions.

Bears and hunters The first installation of rain gauges immediately suffered by chewing from black bears and as targets for hunters. Protective steel drillstem collars were installed in consultation with meteorologists from the Atmospheric Environment Service. The drill stems provided physical protection from both problems. The rims were about 2 cm below the rim of the rain gauges so as not to affect the catch.

Notices were placed at all installations on which the general nature of the study was described, and an invitation was extended to call or visit to obtain further information. These were set up in neatly-designed prefabricated holders to provide some protection from the weather as well as to suggest the seriousness of our approach. Vandalism essentially stopped thereafter except for deliberate theft of some of the flume heating devices and propane bottles.

Designated staff The low-cost approach of operating this project as an adjunct to school activities generally worked well with respect to data collection and maintenance. However, with growth of teaching responsibilities and changing of staff it was not possible to ensure the continuity of data processing and analysis. Despite these problems, data collection on the Whiskeyjack basin has continued to the present.

Access Lack of access made it difficult to complete the installation of all structures on the site in the set-up stage as planned. The use of tracked vehicles and hand labour made it possible to get the work done reasonably quickly before the road system was constructed.

Funds After expiry of the IHD, federal Water Resources participation in the project was reassessed. In 1977, notice was given that completion of gauges were to be discontinued. However, readings and computations have been continued under a federal-provincial agreement with costs shared by both Alberta Environment and Environment Canada for the Whiskeyjack control flume.

Accomplishments

The Whiskeyjack flume is still in place, functioning well, and providing continuing streamflow data. The limitation is that it functions only during the ice-free period of the year. The installation itself is of value in teaching and demonstration.

The weather stations have provided important and extensive data to this project as well as to studies of forest fires and silviculture. The study has provided local data and charts which have been used to advantage in teaching. The streamflow charts clearly demonstrate rises and recessions related to precipitation of various intensities. The streamflow charts also illustrate the differences in response to precipitation between two basins as a result of their respective inherent characteristics. Although the basins are twinned by virtue of their adjacent locations, they are not identical. The differences illustrate both the strength and weaknesses of basin studies, and provide a basis for discussion of why the differences occur.

The data should provide benchmark descriptions of the rainfall-streamflow characteristics of the Whiskeyjack basin. It should be possible to assess whether or not the effects of logging will have induced major changes.

The adjunct surveys of surficial geology, soils, and contours have been of extended value in many other studies.

Perhaps as important an accomplishment has been the demonstrated effective and voluntary cooperation of the nine agencies mentioned previously. The spirit of sharing and learning by doing is worthy of mention.

Impact of results

The existence of the study, activities associated with it, and student involvement in various facets has been an important adjunct to the Forest Technology School programs in conditioning students to the nature and importance of watershed management and erosion control. This has probably been the major impact of the study.

We expect that the data obtained will add in a small way to the body of knowledge in this discipline.

Availability of findings

The data are available for study and research. Unavailability of a designated staff member to be responsible for analysis has been a weakness of the study.

Retrospect

For the objectives of this particular project the basin approach has been appropriate and would be used again. If it were to be done over again, we would recommend the H-type flume at both primary streamflow monitoring locations. Streamflow measurements would be attempted only during the ice-free time of year, focusing primarily on the relationship between streamflow and rain, although snow measurements would be maintained to complete the annual precipitation picture. Measurement of water flows on tributary streams would be done very selectively and with permanent structures. A designated project manager would be selected, and presently-available computer programs would be utilized for records and compilation.

SUMMARY AND CONCLUSION

The Cache Percotte Watershed Basin study fulfilled part of the objectives in one of the basins and is serving a useful role in education and demonstration at the Forest Technology School. The major problems were technical, particularly those of measuring winter streamflow and early spring surges induced by snowmelt. Further problems of ensuring continuity of data collection and analysis may be met through staff assignment and shared funding arrangements.

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The Marmot and Streeter Experimental Basin Programs

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ABSTRACT The Eastern Rockies Forest Conservation Board (ERFCB) was constituted in 1947 in recognition of the special status that the eastern slopes watershed had with respect to water supply in the Saskatchewan River. One of the ERFCB's principal functions was "...the conservation, development, maintenance and management of the forests in such area [the eastern slopes watershed] with a view to obtaining the greatest possible flow of water in the Saskatchewan River and its tributaries." Upon its request, the Alberta Watershed Research Program (AWRP) was initiated during the period 1960-1963 with the establishment of experimental watersheds at Marmot Creek and Streeter Creek to examine the effects of forest cutting on streamflow and groundwater. The results are now available, and models that can be used to predict the impact of forest cutting on water yield throughout the eastern slopes are available to forest and water management agencies.

In spite of this ostentatious beginning and wealth of technology transfer tools, the impact of the Marmot and Streeter projects on water management in Alberta and upon forest management within the eastern slopes watershed is essentially non-existent. The primary reason for this is the changing land use and management pattern within the eastern slopes watershed which, to date, has frustrated all efforts to establish even a pilot-scale watershed management project. Thus, even if water yields could have been quadrupled, it appears that the results will probably will never be applied in the eastern slopes.

This does not mean that the research program has been without benefit. For instance, the Marmot data sets proved valuable for the recreational development for the 1988 Winter Olympics, as the Marmot snow, wind, and temperature data were used in preparing climatologies for the Nakiska ski area. Both Marmot and Streeter have provided valuable hydrologic process and treatment effects data for developing, modifying and testing watershed simulation models. And both areas have been the subject of several MSc. and PhD. theses.

Should the need for another similar program be demonstrated, current technologies in instrumentation and simulation modelling would permit the accomplishment of more with less manpower and in a shorter time period. Experimental watersheds such as Marmot and Streeter should never have been expected to be representative of effects achievable elsewhere nor to yield results that could be directly applied. They should be regarded as places to test models and simulated results of proposed treatments against those

actually obtained in order to establish the credibility of those models for application elsewhere.

RÉSUMÉ Le "Eastern Rockies Forest Conservation Board" (ERFCB) a été créé en 1947 à cause du rôle prépondérant des bassins du versant est des Rocheuses dans la génération des débits de la rivière Saskatchewan. Une des principales fonctions du ERFCB était "...la conservation, le développement, le maintien et la gestion des forêts dans de telles zones [les bassins du versant est] en vue d'obtenir les débits les plus hauts possibles dans la rivière Saskatchewan et ses tributaires." A la demande du ERFCB, le "Alberta Water Research Program" (AWRP), fut initié de 1960 à 1963 avec la mise en place des bassins expérimentaux de Marmot Creek et de Streeter pour l'étude de l'effet des coupes forestières sur les eaux de surface et souterraines. Les résultats de ces études ainsi que des modéles servant à prédire l'impact de la coupe sur les débits dans les bassins du versant est des Rocheuses sont maintenant disponibles.

Malgré le haut profil des bassins de Marmot Creek et de Streeter, et l'abondance des mécanismes de transfert technologique, l'impact de ces projets sur la gestion de l'eau et l'aménagement forestier en Alberta est essentiellement non-existant. La raison première de cet état de chose est que les changements dans les patrons d'utilisation et de gestion des terres ont contrecarré les efforts de mise en place de projets d'aménagement de bassins, même à l'échelle de projet pilote. En fait, peu importe les accroissements de débits démontrés, il semble bien que ces résultats ne seront jamais appliqués dans les bassins du versant est des Rocheuses.

Le programme de recherche n'a toutefois pas été sans bénéfices. Les données de Marmot ont été très utiles aux Jeux Olympiques d'hiver 1988; en effet, les données de neige, vent et températures recueillies sur le bassins ont aidé à planifier la réalisation du centre de ski de Nakiska. De plus, Marmot Creek et Streeter ont fourni des données utilisées dans le développement, la modification et la vérification de modéles de simulation hydrologique. Enfin, ces deux bassins ont fait l'objet de nombreuses thèses de maîtrise et de doctorat.

Si un tel programme s'avérait encore nécessaire, les progrès dans les domaines de l'instrumentation et de la simulation permettraient d'accomplir plus avec moins de personnel et en moins de temps. On n'aurait jamais dû espérer obtenir de bassins tels que Marmot Creek et Streeter des résultats représentatifs d'effets obtenus ailleurs, ou même des résultats pouvant être appliqués directement. En fait, les bassins expérimentaux devraient servir à tester les modèles en comparant les résultats obtenus par simulation à ceux mesurés suite au traitement proposé, de façon à établir la crédibilité de ces modèles pour leur application à d'autres bassins.

NEED FOR RESEARCH

The eastern slopes of the Rocky Mountains in Alberta have long been recognized as an important watershed (Laycock, 1965). The Eastern Rockies Forest Conservation Board (ERFCB) was constituted in 1947 in recognition of the special status of this area with respect to water supply in the Saskatchewan River, which is vital to the water needs of southern Alberta and Saskatchewan. One of the ERFCB's principal functions was "...the conservation, development, maintenance and management of the forests in such area [the eastern slopes watershed] with a view to obtaining the greatest possible flow of water in the Saskatchewan River and its tributaries" (Canada, 1947). "How to manage this watershed for water production and water supply protection" was a question faced by the ERFCB. Upon its request, the joint provincial-federal Alberta

Watershed Research Program (AWRP) was initiated during the period 1960-1963 with the establishment of experimental watersheds at Marmot Creek and Streeter Creek to examine the effects of forest cutting on streamflow and groundwater (Jeffrey, 1964, 1965).

OBJECTIVES

1. To provide climatic data in sufficient temporal and spatial resolution so that the impacts of forest cutting activities on microclimate and streamflow could be determined.
2. To investigate means to increase the quantity of runoff from the eastern slopes.
3. To ascertain if the streamflow hydrograph could be flattened out to obtain the same, or greater, quantity of snowmelt runoff over a longer period of time.
4. To determine if the harvesting guidelines of the Alberta Forest Service (AFS) (Alberta, 1971) for commercial cutting in spruce-fir forests were satisfactory for maintaining the volume of high quality-water that these watersheds yield.
5. To propose and test harvesting options specifically designed to alter streamflow.

Originally a similar set of objectives existed for Streeter Basin, but later these were reduced to a single more realistic objective of determining the effect of tree clearing above West Streeter spring upon its water yield and regime.

RESEARCH APPROACH

Rational for research basin approach:

The research basin approach was the technique most widely used and accepted for watershed management research at that time. Results from plot studies could be qualitatively interpreted, applied as forest cutting experiments, and quantitatively evaluated as an effect on streamflow.

Small watersheds or research basins were thought to be more representative of spatial variation than plot studies. The effect on streamflow was an integration of many individual soil, topographic and microclimatic situations.

Hydrologic simulation models were just beginning to appear on the research scene, and were not widely accepted as a valid way to emulate the behaviour of a complex watershed. If and when suitable models became available, the data from research basins could be used to test them.

Why were Marmot and Streeter chosen:

Marmot Marmot was chosen because it is a representative of the subalpine forest type. The subalpine vegetation type occurs just below timberline where snow accumulation is high and streamflow occurs throughout most of the snow-free season. Marmot's subalpine classification (Rowe, 1977) places it in the same vegetation-climate classification as the better-known Fool Creek watershed on the Fraser Experimental Forest in Colorado (Alexander & Watkins, 1977).

Streeter Streeter was chosen because it a representative of the aspen-grassland vegetation type. These grasslands are important to the ranching economy of the foothills of southern Alberta, and they occupy a significant portion of the Saskatchewan River headwaters. The woody vegetation (primarily *Populus* and *Salix* spp.) of them has been periodically removed to allow greater grass production and more grazing capacity. These clearing activities were thought to have an unknown but potentially serious impact on water yield, regime, and quality.

TOPICS RESEARCHED

Climate and Meteorology:

Emphasis during the early stages of the program was on the spatial variability of the monitored parameters. These included:

- A study to estimate precipitation variability over the basins.
- A series of raingauge intercomparison studies in mountainous terrain.
- An estimate of the variability of wind and temperature fields over the Kananaskis Valley.
- An estimate of radiative fluxes over the various topographic aspects of the watershed.
- An estimate of turbulence characteristics within the watersheds.
- A comparison of snow pillow and precipitation gauge measurements.
- An examination of the correlation between snow accumulation and elevation.
- A computation of water balances over the sub-basins.
- An evaluation of the impact or forest cutting practices on snow accumulation.
- An evaluation the influence of tree cutting patterns on windflow.

Hydrology:

- The evaluation of several streamflow watershed models. One of the models tested was the UBC watershed model and the wealth of data in the basin provided for a rigorous analysis and calibration of the model.

Forest cutting/water interactions:

- Effect of specialized forestry operations on annual water yield and seasonal streamflow (Marmot, Twin subbasin).
- Effect of commercial forestry practices on erosion and sedimentation (Marmot, Cabin subbasin).
- Effect of forestry practices on inorganic water quality.
- Hydrologic processes effected by forest cutting:
  - Local precipitation distribution and disposition.
  - Soil moisture and temperature.
  - Snow accumulation and melt.
  - Transpiration and evapotranspiration.
  - Subsurface water storage.
  - Soil water flux.
- Derivation and testing of simulation models (Dickinson, 1982).

DIFFICULTIES AND STUMBLING BLOCKS

The biggest stumbling block was a lack of knowledge of the time and resources that would eventually be required to complete the project. Some of the co-operative agencies were led to believe that the project could be completed in ten years: five years evaluation in the natural state and five years evaluation following treatment. It became apparent somewhat later that this 10-year time frame was unsuitable and there are some of us that contend that the eventual 25-year life of the project was not adequate because a forest cutting experiment should be run from prior to cutting the original forest to the same state in the replacement forest. This takes 80 to 200 years in Alberta. It does not mean that results cannot be used prior to the completion of the study, but it is not possible to estimate the duration of a treatment effect without some measure of that duration. Obviously a 25 year study is short term considering the long replacement time in this climate.

Other cooperators were led to believe that timber sale revenues would finance the harvesting, and were unprepared for requests for funding to subsidize the harvesting of timber from areas too small or on terrain too steep to make logging a paying proposition. It must be recognized that treatments cannot ordinarily be done without cost. Agencies set aside funds for personnel and equipment to evaluate a treatment and must be aware that they will also have to pay to have timber cut in an appropriate pattern.

Treatment plans must be clearly understood and agreed to by all participants. This was not always the case in Marmot and Streeter. A watershed treatment should be viewed as a single experiment. The plan must be fixed early in the experiment so that evaluation measures can coincide with both the spatial and temporal activities associated with the implementation of the treatment. If the treatment is subject to frequent review and change, then the evaluation will be difficult if not impossible.

The maintenance of equipment and the maintenance and quality control of databases are always areas of concern in meteorological studies. This program in particular was not immune to these problems as the rather ambitious monitoring was operated in an era when recording devices, the availability of manpower, especially students during the winter season, all proved to be major difficulties. Extraction of data from chart recording devices was also manpower intensive although much of the data was ultimately placed in computer-processible media.

Some data sets proved extremely difficult to collect. For example, wind measurement studies at higher elevations and estimates of snowpack in the alpine proved to be particularly troublesome.

The financial resources that the various agencies could devote to the project were severely reduced in 1978 as a result of a departmental "A Base Review" which forced the Atmospheric Environment Service to withdraw most of their services. Although key meteorological sites were maintained, this withdrawal created a data gap that could not be filled by any alternative means. Also, there was a lack of commitment by some of the early participating agencies which led to their termination of activities at an early date.

A conflict existed between ease of access, operability and representativeness in the selection of Marmot. Early in the program it was realized that Marmot might not be the most representative basin, but that the proximity of the Kananaskis Forest Research Station made it attractive from an operational aspect. However, Marmot contained a marginal amount of timber to cut, in that 40 to 50% of the basin is alpine and not harvestable. Furthermore, about 40% of the timbered area was at an elevation where harvesting was prohibited by regulations (which were waived for the Cabin Creek treatment).

Conflict with changing forestry operations. It takes 10 to 15 or more years of records after calibration and treatment to evaluate the effect of a forest clearing operation on streamflow. By the time the results are in, the practice being used may have changed. For instance, commercial practice at the time Marmot was started was to completely clear all standing timber from a cut block. By the time Cabin Creek was clear-cut, the practice was to leave non merchantable trees standing. These two differ in the microclimate and energy transfer characteristics at the snow and underlying vegetation surfaces.

Numerous other operational problems were encountered. For example:

- During the latter period of the study, 'glaciation' occurred at the Cabin Creek hydrometric station, which led to some record loss during low flow periods.
- Hydrometric stations were much more difficult and expensive to install than originally envisioned.
- As time progressed, rehabilitation work was required on some of the control structures, and if not carried out promptly, some record loss was incurred.
- A coal lease existed in Marmot which threatened its existence as a research area.
- Lastly, an area adjacent to Marmot was selected for the 1988 Olympics. Although the Olympic site was completely outside of Marmot, the Province's desire to allow for expansion of the ski runs into the watershed forced Marmot's closure in October 1986.

ACCOMPLISHMENTS

The extensive hydrometeorological data sets for the basin (Davis, 1964) were very useful in testing and calibrating watershed simulation models. The major benefit to the Water Resources Branch, which originally wasn't envisioned, was acquiring an excellent knowledge of various control structures, and enabled the Branch to improve its operational capabilities, both locally and nationally.

An aspect which can be readily overlooked is the personal contact benefits of a multi agency project. These contacts, which have been generated over a period of 25 years, have been very beneficial to the majority of participants in the research basins.

The Marmot Creek Basin has also served as a showplace for international and national visitors, although the magnitude of the project may have led some to believe that much more was being accomplished than actually occurred.

For the most part, the meteorological studies (Ferguson & Storr, 1972) successfully achieved their objectives (Storr, 1977). The precipitation data were successfully analyzed to show the relationship between snowpack accumulation and altitude (Golding, 1974), and similar relationships between evaporation and elevation were also demonstrated.

Photogrammetry proved to be somewhat successful for estimating the snow in Marmot basin and a new technique was developed to extract radiation data from recording charts (Storr, 1972). In experiment undertaken to examine the siting of precipitation gauges in mountainous terrain, Storr (1966) found that the criteria recommended by the World Meteorological Organization resulted in serious undercatch of precipitation in the Marmot Basin.

Clear-cut harvesting of 23% of the area of the Cabin Creek subbasin of Marmot in 10 ha commercial-sized blocks increased annual water yield by 35.7

dam^3 (17 mm) or 6% greater than predicted if left uncut (Swanson *et al.*, 1986). Erosion was not a problem on the stable soils of Cabin Creek; neither did suspended sediment load increase as a result of this timber harvest.

Clear-cutting 50% of the vegetated portion of the west subbasin of Streeter in a pattern designed to augment snow accumulation and retention of snow on site increased water yield from a small contact spring, during April through October, by 6.3 dam^3 (82 mm) or 175% more than predicted if left uncut (Swanson *et al.*, 1986). More importantly, flow continued throughout the summer of 1977, the second driest year on record in southern Alberta, even though predicted flow was zero if left uncut.

IMPACT OF RESULTS ON WATER MANAGEMENT

There is a conflict within this research program, and among the coauthors of this paper, as to the objectives of the Marmot, Cabin Creek subbasin treatment and the statistical significance of the results. Differing interpretation of the treatment and its results continue to affect the way the results are viewed and used by research agencies and water management agencies.

The Research Coordinating Committee, under whose auspices the Cabin Creek treatment was conducted, changed the objectives of this treatment from one to evaluate the effect on water yield and sediment to one of sediment only. This was done because the members of the committee recognized that the area to be treated on Cabin Creek was small, and that the statistical errors in evaluation were large, so that an effect on streamflow would be difficult if not impossible to detect. We also recognized that variation in sediments must be large if they are to be detected as the errors in measuring sediment are normally greater than those in measuring streamflow.

On the other hand, the effect on streamflow was a major objective of the program that had to be met. The research coordinator (Swanson) felt that data from the Cabin and Twin Creek treatments could be combined with data from plot studies done elsewhere in Alberta, Canada and the United States, to derive a simulation model to meet the "effect" on streamflow objective.

The selection of Mount Allan as the site for the 1988 Olympics, and the threat to the research program that this selection posed forced premature evaluation of the Cabin Creek treatment. An extended period of below normal snowfall years following treatment, fairly high standard errors in the paired watershed regressions and the 1986 closure of Marmot prevented us from obtaining a sufficient number of years of data (Kovner & Evans, 1954) to conduct a satisfactory statistical evaluation of either the Cabin or Twin Creek treatments. However, statistical evaluation of the Cabin Creek data was attempted, but at a lower confidence level (80%) than that normally used in research studies (95 to 99%, Freese, 1967), by Swanson *et al.* (1986), who determined that an increase in yield of 17 mm was statistically significant at the 90% level. The same data were examined under contract from the Water Resources Branch by Hydrocon Engineering (Continental) Ltd (1985), who concluded that the increase in streamflow on Cabin Creek was not statistically significant at the 95 to 99% level, and therefore was non existent.

Thus one major point of contention within the Marmot program is whether or not streamflow on Cabin creek was actually increased by the clear-cutting that occurred. Since the treatment of Cabin was intended to emulate existing commercial harvesting practice and not to optimize water yield and the evaluation period was curtailed, those of us in research were delighted that an increase could be detected at any reasonable level of probability. We all agree that the increase that occurred as a result of the Cabin Creek treatment is physically insignificant in terms of water management of the eastern slopes.

On the other hand, those of us in research contend that clear-cutting specifically designed to increase water yields would produce physically significant gains in streamflow from the eastern slopes watersheds. The WRENSS (Troendle & Leaf, 1980) procedure simulates increases of 50 to 60 mm over most of the eastern slopes watershed if 1 hectare clearings are created (Swanson & Bernier, 1986). The simulated increase in yield with 1 ha clear-cuts is roughly 3 times the 17 mm observed at Cabin Creek where 10 hectare clearings were created, approximately 2 times the 41 mm obtained from 16 to 1400 ha clear-cut under a primarily spring rain dominated precipitation regime at Hinton, Alberta, (Swanson & Hillman, 1977) but somewhat less than the 80 mm observed at Streeter Basin where 1/2 hectare clearings were created. WRENSS simulations for Streeter, Hinton and Marmot Cabin are 82 mm, 33 mm and 11 mm respectively.

Regardless of the foregoing, the bottom line is that the impact of the Marmot and Streeter projects on water management in Alberta and within the eastern slopes watershed is non-existent. The primary reason for this is the changing use and management pattern within the eastern slopes watershed, which to date has frustrated our efforts to put in place a recommended (Northwest Hydraulics Consultants Ltd., 1977) demonstration or operational watershed management project (Bernier & Swanson, 1986). We realize that land managers in the eastern slopes watershed must consider uses other than water production when making decisions. It is presumed to be more expensive to harvest timber from the small clear-cuts that our's and other's results (Leaf, 1975; Troendle, 1983) indicate to be most effective in enhancing water yield than from those presently used. An economical means to harvest timber in order to maintain a supply of logs for the wood products sector of the economy continues to be important in Alberta. It is likely that recreational use and the maintenance of wildlife habitat within the eastern slopes watershed will assume increasing importance in the future. Many areas of the watershed that could have been managed for water yield improvement have already been harvested in the less-efficient (for water yield increase) larger clear-cuts and a new stand of merchantable trees will not be available for 100 or more years. Other areas are being set aside for uses not compatible with any type of timber harvesting. Therefore, even though water yield improvement is technically feasible, it is extremely improbable that forest cutting specifically designed to augment water yields from the eastern slopes will ever take place.

AVAILABILITY OF RESULTS

Hydrology:

All streamflow data is available in the annual "Surface Water Data Alberta" publications produced by Environment Canada (e.g. Water Survey of Canada, 1987a & b). These data are also available on tape and microfiche. A limited quantity of the annual compilations of hydrometeorological data are available for Marmot for the years 1962 to 1980, and for Streeter for the years 1964 to 1977, from Canada Water Resources Branch, Calgary.

Climate and meteorology:

The meteorological data sets have been archived and a documentation of their status was completed by Mann (1984a). The studies were well documented in the proceedings of numerous hydrology workshops and various Western Snow Conferences, as well as in several refereed journals. A comprehensive survey of all of these reports was completed by Mann (1984b).

Forest cutting/water interactions:

The WRENSS procedure (Troendle & Leaf, 1980) has been tested against Marmot Cabin Creek and Streeter Basin data. This procedure provides an objective way to propose and evaluate the effects of various forest clear-cutting treatments on annual water yield. It has been programmed for use on a microcomputer (IBM PC compatible; Bernier, 1986) and is available upon request from the Canadian Forestry Service, free of charge.

The results of clear-cutting portions of the Marmot Cabin Creek and Streeter Basin watersheds, and the streamflow data upon which those results are based, are available in a single publication (Swanson et *al.*, 1986). Most of the research done on Marmot and Streeter Basins were catalogued in a symposium proceedings in 1977 (Swanson & Logan, 1977). We plan to publish an updated annotated bibliography in the near future. At the present time, these combined research basin programs have resulted in over 87 published reports.

ARE RESULTS BEING USED?

Hydrology:

The data have been used to conduct watershed modelling studies. It has also been utilized to make the decision that the results can't be used operationally to increase water yield on the eastern slopes.

The major use has been by university students. Countless numbers of requests were filled for these users, who utilized the information for papers and theses.

Climate and meteorology:

The Marmot data sets have proven valuable for the recreational development which proceeded subsequently in the Kananaskis Valley. Most of this work has focused on preparations for the 1988 Winter Olympics, and the Marmot snow, wind, and temperature data have been used in preparing climatologies for the neighbouring Nakiska ski area. In addition, the development of techniques used in the weather forecasting program for the ski area would have been much less successful than they were had the 20-year Marmot database and the resultant research reports been unavailable.

Forest cutting/water interactions:

Yes, the results are being used primarily for model development and verification. Both Marmot and Streeter have provided valuable hydrologic process and treatment effects data for developing, modifying and testing watershed simulation models. The most fully developed model application is the simplified WRENSS (Troendle & Leaf, 1980; Bernier, 1986) procedure which is currently being used by the Alberta Forest Service to estimate the effects of various controversial harvests on streamflow. WRENSS is also being used to design or evaluate treatments in other situations where forest cutting is being considered as one of several alternatives to augment water yield, e.g. Nenosee Lake watershed in Saskatchewan.

WOULD YOU DO IT ALL THE SAME AGAIN?

Hydrology:

It is obvious that the answer is no. From a water management agency's perspective, the most significant negative is that even if water yields could have been quadrupled, the results probably couldn't be applied.

Climate and meteorology:

From the meteorological perspective the answer is maybe. Monitoring technologies have improved markedly since the Marmot and Streeter programs were started. Should the need for another similar program be demonstrated, current technologies would permit accomplishing more with less manpower. This was in fact recently proven during the 1988 Winter Olympics when an extensive wind and precipitation network was established on the southeast shoulder of Mount Allan and successfully operated essentially unattended for the last two years. Remote sensing technologies and reliable hardware have greatly reduced manpower needs for programs of this type.

Forest cutting/water interactions:

From the forestry research perspective the answer is no. There was no firm commitment by the forest management agency to implement water yield improvement practices within the eastern slopes watershed. Furthermore, it has taken so long to obtain locally-derived results that the management opportunities have slipped away. The science of forest hydrology was well enough advanced in 1960 so that a cutting pattern could have been proposed and tested as a pilot treatment. The advice of those experienced in watershed management research in the United States was to initiate such a pilot program, using a cutting pattern similar to that on the Fool Creek watershed in Colorado. Our findings still point to this type of cutting pattern as being the most suitable for application to increase water yield from the subalpine and foothills forests. In retrospect, this advice should have been followed. Fortunately for us, none of the current research or management personnel were part of the decision process at that time.

In 1960, no acceptable hydrologic simulation model was available. This has changed radically since then. We now have a number of reasonably good models to choose from. If starting again, we would recommend that we adopt one of these and develop it as a tool for transferring the results of small watershed and plot experiments to operational situations. The emphasis would be on making the model usable with a minimum amount of data on ungauged watersheds. Experimental watersheds such as Marmot and Streeter would not have been expected to be representative of any particular zone, but would be regarded as places to test simulation results from proposed treatments in order to establish the credibility of the model.

The Marmot and Streeter basin studies provide contrasting examples of how not to approach a research study, i.e., to choose research sites without due and full consideration of all of the ultimate research objectives. In the case of Streeter, a poor choice was overcome by modifying the objectives to make them fit the physical realities of the basin. However, the physical problems encountered in Marmot were not as readily evident as those in Streeter, and even though the Cabin Creek treatment objectives were modified to meet research objections, the modifications were not totally agreed to by the management agencies involved.

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The Spring Creek research basin (Alberta)

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ABSTRACT The Spring Creek research was undertaken to provide information on a number of pressing questions. First, the research program was to investigate the effects of land use change (from pristine boreal forest to highly developed agricultural farm land) on the hydrological cycle. Secondly, the research program was to provide regional hydrometeorological data in an area where these data previously did not exist. This information was required to provide information on the management of water resources and to provide design parameters for water resource projects.

The Spring Creek research basin encompasses 112 square kilometres and is located in north-western Alberta. The research program was initiated in 1965 by Alberta Agriculture, Water Resources Division and later transferred to Alberta ENvironment in 1972. The research formed part of the International Hydrologic Decade (1965 to 1975).

The Spring Creek research program has had problems and successes. During the pre-treatment phase of the research, the basin provided a good, well documented data set for the region. The research has resulted in the development of the Storage-Effective Drainage (SED) runoff model, which is based on accurate accounting of basin storage. The SED model is an innovative approach to hydrologic modelling and is considered a break-through in hydrology. This model provides a tool to assess land use change in the post-treatment phase. The problems experienced in completing the research mandate are discussed under four categories. These four categories are practical, physical, political, and financial problems.

This paper provides an overview of the Spring Creek research program. It outlines the objectives of the research, the results, problems, and provides a critical overview of the research basin approach.

RÉSUMÉ La recherche sur le bassin de Spring Creek a été initiée afin de répondre à des besoins pressants. Le programme de recherche devait d'abord se pencher sur les effets du changement d'utilisation des terres (de forêt boréale non-perturbée à une agriculture intensive) sur le cycle hydrologique. Le programme de recherche devait aussi fournir des données hydrométéorologiques pour une région où ce type de données était inexistant. Cette information était nécessaire à la gestion des ressources hydriques ainsi qu'à l'établissement des critères de conception pour les projets de gestion de l'eau.

Le bassin de recherches de Spring Creek couvre 112 kilomètres carrés dans le nord-ouest albertain. Mis en place en 1965 par Alberta Agriculture, Water Resources Division, le programme de recherche a été transféré à Alberta Environment en 1972. Le programme a été inclus dans le programme de la Décennie Hydrologique Internationale (1965-1975).

Le programme de recherche de Spring Creek a connu succès et échecs. Au cours de la phase pré-traitement, le bassin a fourni une excellente base de données pour la région. La recherche a mené au développement du modèle de

simulation de l'écoulement "Storage-Effective Drainage" (SED), modèle basé sur le suivi exact de l'emmagasinement de l'eau sur le bassin. Le modèle SED représente une approche innovatrice à la modélisation, et est considéré comme une percée en hydrologie. Ce modèle peut servir à l'évaluation de l'impact hydrologique des changements dans l'utilisation des terres au cours de la phase post-traitement. Les problèmes qui entravent l'exécution du mandat de recherche sont regroupés en quatre catégories: pratiques, physiques, politiques et financiers.

Ce texte offre un survol du programme de recherche de Spring Creek, ses objectifs, ses résultats et ses problèmes, et comprend une discussion critique sur l'approche par bassin de recherche.

INTRODUCTION

The Spring Creek Research basin was established in 1965 as one of the projects of the International Hydrologic Decade, which ran from 1965 to 1975. Hydrometeorological measurements commenced in the summer of 1966 and continued until the basin was closed in 1987. The last measurements were taken on October 31, 1987. The basin, which has a catchment area of 112 square kilometres, is located in northwest Alberta approximately 30 kilometres southwest of the Town of Valleyview. The creek is a right bank tributary of the Simonette River, which is a sub-basin of the Peace River.

The research basin is heavily wooded, the forest cover, consisting predominantly of deciduous trees, mainly aspen with some black and white spruce, accounting for approximately 70 percent of the basin. Swamps and muskeg extend over 25 percent of the total catchment area, with lakes and beaver dam reservoirs accounting for a further 3 percent. The land within the basin is gently sloping with elevations ranging from 790 meters in the headwaters, down to 610 meters at the outlet. The Spring Creek basin has a mean annual precipitation depth of 520 mm and a mean annual evapotranspiration depth of 427 mm. The mean annual runoff depth is approximately 93 mm.

Hydrometric data were collected at 7 sites, with the majority of the stations running from 1967 to 1987. In addition to the hydrometric data, precipitation data; including snow pillows and snow courses, temperature data, humidity data, and a limited amount of groundwater data were also collected. Due to the large size of the basin, the gauging network had to be sufficiently dense to account for the inputs and outputs of the basin.

RESEARCH MANDATE

During the 1950s and 1960s, new lands were being developed for agriculture at a rapid rate, particularly in north-western Alberta. It was the concern of the Water Resources Branch, Alberta Department of Agriculture, that this rapid conversion of virgin lands to agricultural lands was altering the natural hydrological characteristics of these areas. These changes were often to the detriment of the people carrying out the development. Therefore, the Spring Creek Research program's main objective was to identify the effects of agricultural development; specifically, the effects of large scale deforestation of a pristine boreal forest on the hydrologic cycle.

THE RESEARCH BASIN APPROACH

There were three main reasons why the research basin approach was chosen to investigate the impact of deforestation on the hydrologic cycle. The most significant reason was that, during this period, research basins were the "state of the art" approach to research. The International Hydrologic Decade was a time when the spirit of cooperation in expanding hydrologic knowledge flourished, and consequently, many of the research watersheds were established during the decade. These projects provided a life size laboratory in which researchers could pursue the objectives of their investigations. The Spring Creek Research basin formed on of the many International Hydrologic Decade projects. Secondly, this approach allowed the use of a paired basin investigation within the region where development was occurring. This method appeared to be the best means to assess the impact of the large scale land use changes that were taking place. The third reason, was that it provided a logical means of not only satisfying the objectives of the research, but also provided a hydrologic data set where no data previously existed.

The Spring Creek basin was chosen because it was a virgin parkland area that was on the fringe of the lands that were being opened for homesteads. This land was crown land, and therefore, under provincial control and the basin was in a region of unknown hydrologic characteristics.

RESEARCH TOPICS WITHIN THE SPRING CREEK RESEARCH BASIN

There have been many research topics addressed in the Spring Creek basin. The following is a partial list of these topics.

(a) The original topic of research for the Spring Creek basin was "how do changes in land use alter hydrologic responses."

(b) Hydrograph separation in surface and subsurface flows were investigated using isotopic radioactive tracers in snowmelt processes on a six hectare sub-basin within the Spring Creek watershed (Holecek & Nou Jaim, 1975).

(c) The same sub-basin was used to evaluate the runoff characteristics of the snowpack in the pre-treatment phase (forest) and the post-treatment phase (pasture grass) (Holecek, 1980).

(d) This sub-basin was also used to evaluate changes in groundwater regimes in the before and after treatment phases (Ryckborst, 1981).

(e) From 1980 to 1987, the prospects for determining basin storages from water balance analyses were studied. Physical modelling of the runoff processes is impossible without this parameter. The procedure chosen was to instrument the basin for parameters that would calculate F.I. Morton's Complementary Relationship Areal Evaporation (CRAE) model (Morton, 1978). With evaporation independently measured, the basin's water balance was established.

Basin storage = Precipitation - Runoff - Evaporation

As a consequence of the successful application of this procedure, the development of the Storage-Effective Drainage (SED) runoff model was developed (Holecek, 1988). A more extensive review of the background material and SED concepts are found in an Alberta Environment internal report on the Spring Creek basin entitled, "Spring Creek Project - Phase One - Final Report" (Holecek, 1985).

(f) Several proposals were developed for the treatment phase - Phase II of the research program (Holecek, 1974; Card, 1977; Davies, 1985).

In addition to these topics, precipitation throughfall, sediment yields, and basin inventories were also studied. These and other reports are listed in the bibliography.

OBSTACLES AND DIFFICULTIES IN ACHIEVING THE RESEARCH OBJECTIVES

There have been many obstacles in achieving the objectives of the research program. These difficulties can be broken into four categories; practical, physical, political, and financial.

The practical difficulties of research and research basins are by far the greatest to overcome. In terms of the Spring Creek basin, it had been projected that development within the basin would occur within 15 years of the project's inception. Now, some 23 years later, development still appears to be 15 to 20 years in the future. Without this development, the main objective of the research program cannot be achieved. It is beyond the project's funding to develop the land independent of the natural process. While investigations and proposals have been made to develop the lands, the costs are extremely high and the benefits do not seem to justify this expenditure in the current fiscal climate prevailing in Alberta.

While the lack of development within the basin proved to be an obstacle to attaining the main objective of the research, it saved the program from encountering a stumbling block so common to many research endeavors. Research is by its' nature an investigative process, trial and error, and an exploration of new ideas. To place time and budget constraints on it often leads to research projects that are inconclusive, incomplete, or inaccurate in their findings. Had the treatment phase proceeded within five to ten years of the program's inception, one of the most serious practical problems of the research program would not have been resolved. ALso the major achievement of the research to date would not have been realized.

The most trying practical problem encountered during the pre-treatment phase of the research was how to compare paired basins, with sufficient accuracy, to be able during the treatment phase to distinguish between the impact of the treatment and errors in the investigative tool. Having explored regression, statistical, and even crude physical modelling, it became increasingly apparent that a knowledge of the basin storage conditions were essential. This parameter is needed before any accurate physical modelling of the pre-treatment basin can be accomplished. Without the ability to identify accurately what would have occurred naturally, it is impossible to conclusively determine the impact of the land use change. With the advent of F.I. Morton's (1978) method of computing areal evapotranspiration, major breakthroughs in the research became a reality, as basin storage could be established with some degree of definitiveness. The extended pre-treatment phase allowed sufficient time to develop the necessary tools to proceed to the treatment phase of the project.

The Spring Creek experience in retrospect, illuminates a more subtle practical problem experienced by many researchers. To establish a definitive timetable and terms of reference at the beginning of a research program, may be the single greatest practical problem a researcher faces. A definitive timetable and terms of reference often places the researcher in conflict with the program administrators. If a five year pre and post treatment phase has been established, this program may continue independently of the direction and progress of the research. Research must be goal oriented. However, the research program must be evaluated, and re-evaluated, in terms of the investigative process, and the program planned in light of previous successes and failures. This is the nature of research. Administrators must recognize that the need to fund projects based on the merit of the research proposal, and direction, rather than as an all or nothing, one shot, endeavour.

Physical difficulties are the experience of every researcher who has worked in a research basin. Roads have to be constructed and maintained. During the early years, access to the gauges proved to be extremely difficult and time consuming. There were major problems with vandalism to the instrumentation, which ranged from hunters shooting the rain gauges or urinating in them, to moose eating through the manometer tubing of a snow pillow. Icing of the flumes and weirs each years required hours of steaming and chopping to prevent back water. Beaver dams and dam breaks were a constant concern. Contaminated gravel, for road maintenance, necessitated hours of weed pulling. A flood and the poor maintenance of a debris boom, resulted in a pipeline crossing failure. This failure produced a surge wave which devastated the main gauging station and local channel. These problems, though frustrating in nature, were overcome by the dedication and persistence of a good field crew, and the continuing support of the project managers and administrators.

Political difficulties that were encountered arose generally from conflicts in the desired land use of the Spring Creek basin. The basin is in an area that is regarded as "geologically hot". Therefore, there were constant requests for seismic exploration and development of wells. This type of uncontrolled development would have jeopardized the obtaining of meaningful results from the research. It was found that by being as accommodating and as rigorously consistent as possible in our policies concerning development and exploration, and in the use of the roads, we were successful in preserving our interests as each conflict arose.

Fiscal difficulties were an ever present problem. It is difficult to justify the expenditure of capital if the benefits are not readily or clearly definable. This often necessitated the use of homemade equipment, which often worked well but occasionally failed miserably. It should be stressed that providing more money to a project, will not necessarily produce results and often may be a detriment. However, the day to day operations of the Spring Creek basin were well funded, and as a result the quality of the data collected is good. The main objective of the Spring Creek research program, in a basin this large, can not be funded independently of the natural development process. The treatment phase of the basin was expected to occur in a controlled natural manner, not from funding allocated to this purpose. This did not happen. The total funds required for the operation of a research project should be clearly identified. This should ensure that project planning can be completed and that these plans can be implemented.

SPRING CREEK RESEARCH PROGRAMS ACHIEVEMENTS

There have been a number of achievements as a result of the research activities within the Spring Creek basin. The most notable of which is the SED model (Holecek, 1988). During the research pre-treatment phase it was observed that;

- during two consecutive water years the basin had a 50 percent difference in annual input but displayed a 700 percent difference in annual output and,
- two storms, with virtually the same magnitude and intensities, generated output responses that differed by a multiple of 500.

Given the wide range of watershed response to a given input, and the non-linearity of the relationship to output, it obviously would be impossible to distinguish the effects of deforestation using established investigative tools of regression and statistical analyses. Research during the pre-treatment phase indicated that the errors associated in relating two paired watersheds to each other could easily mask the impact of a land use change using these traditional tools. It was essential to develop a means of accurately recreating the natural flow hydrograph in terms of both volume and shape. WIthout this ability, the impact of the treatment could never be conclusively determined and the main objective of the research program attained.

The ability to compute accurate basin water balances, and therefore, to account for storage within a basin, is considered to be of major importance and led to the development of the SED model. The SED model, which uses the basin storage condition to provide a means of accurate runoff modelling and hydrograph reconstruction, is an accurate model to compare pre and post treatment conditions. This model is capable of single event and seasonal modelling. (See Appendix for information outlining the development of the SED concept, three methods for obtaining the SED relationship and displaying the results.)

With the development and varification of the SED model, the Spring Creek program successfully achieved the goals of the pre-treatment research. With the extended pre-treatment phase, the basin has experienced a full range in hydrologic conditions from very wet to very dry, and therefore, the impact of deforestation can be addressed for this full range.

The Spring Creek research activities provided a good hydrometeorological data set where no data were previously available. This data set has been used extensively within the region for a wide variety of designs and hydrologic investigations. These well documented data provide a good basis for research past, present, and future.

THE PERCEIVED IMPACT OF THE RESEARCH ACHIEVEMENTS ON THE MANAGEMENT OF WATER RESOURCES IN CANADA

We expect that the importance of a basin water balance in the study of hydrologic variability will be recognized and used as a basis for comparing project results among experiments and adjacent basins.

Further we expect storage variability to become an important parameter in analyses of input to output runoff relationships. To accomplish this implies the need for a reliable independent estimate of evaporation.

Finally, we expect the SED concepts to become a useful tool in analyzing environmental changes that cause altered hydrologic responses.

CRITICAL OVERVIEW OF THE RESEARCH BASIN APPROACH

A major concern of all those involved in research is with definitive results versus the cost of attaining those results. This concern immediately places the two major participants in the research in conflict. The administrator concerned with the funding and costs of a project, wants to know when he will get his answer and how much it is going to cost. The researcher concerned with the investigation and exploration for the result, wants to know how long he has to get his answer and when will his funding end. This natural conflict will continue, but, it must not be allowed to jeopardize the technique used in the research process.

Research is by its' nature, trial and error, investigation, and exploration of new ideas. It is essential that research be goal oriented, however, it can not be stifled by preconceived timetables and techniques. One of the practical problems of the research basin approach is that the timetables and the research techniques are often established prior to the onset of the research program. This leads to an all or nothing, one shot, here today gone tomorrow approach to research. The Spring Creek Research basin did not follow the preconceived timetable as development did not occur as quickly as was predicted. This deviation from the projected timetable allowed the researchers time to investigate the preconceived research technique, the paired basin approach, only to find this approach inadequate to meet the overall objectives of the research program. As a result, the research produced a major breakthrough in its' pursuit of the overall objectiva of assessing land use change, the SED model, a tool capable of measuring this change.

There are therefore, important lessons to be learned by the Spring Creek experience. The researcher must remain flexible in the research program can not be preconceived in its' entirety, it must be developed based on the evaluation and re-evaluation of past success and failures. In the research program there must be a goal, and therefore, there must be a path or direction maintained in pushing forward to attaining this goal in a step-wise fashion. There is a need to look for external solutions to problems encountered during the research and therefore the communication of both successes and failures is essential. With this need to communicate comes the responsibility of following strict scientific methodologies to ensure we are not led astray or lead others astray. It is essential that data are collected correctly, archived properly, and accessible to others.

In regard to the funding of the project it is essential that the day to day operations of the basin be adequately funded to ensure the quality of the data. The funding of the research should be based on the merit of a proposal and the direction of the research rather than on a single result oriented approach. There is a need to promote the value of research and to publicize its' successes to ensure the continued support of those funding these projects and to point out the costly errors of designs which are potentially over or under sized.

If faced with the same research problems today, it is unlikely that the research basin approach would be adopted. Because of the high cost of establishing and maintaining a research basin the size of the Spring Creek watershed, the project would not be approved for funding. The question that remains unanswered is what are the alternatives to this type of research.

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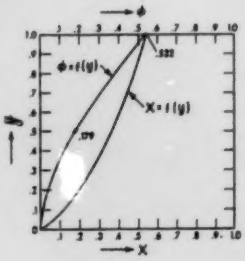
APPENDIX

THE SED MODEL (1 OF 4)

BASIN STORAGE VS EFFECTIVE DRAINAGE

'SED' MODELLING

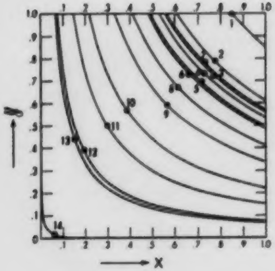
DEVELOPING THE 'SED' CONCEPTS



STEP 1

OBSERVE

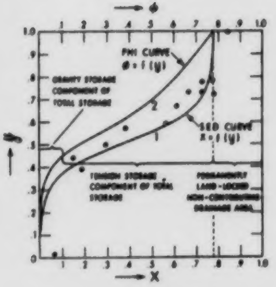
1. THE RELATIONSHIP OF STORAGE 'Y' VS EFFECTIVE DRAINAGE 'X' OVER THE FULL RANGE OF BASIN STORAGES
2. USING 3 POINTS (MAX., MEAN, MIN.)
3. PLOT THE RELATIONSHIPS:
   STORAGE 'Y' VS RUNOFF COEFFICIENT 'PHI'
   STORAGE 'Y' VS STORAGE 'Y' TIMES RUNOFF COEFFICIENT 'PHI'



STEP 2

OBSERVE

1. THE RELATIONSHIP OF STORAGE VS EFFECTIVE DRAINAGE OVER THE FULL RANGE OF BASIN STORAGES
2. USING 14 POINTS
3. PLOT THE RELATIONSHIP:
   RUNOFF COEFFICIENT VS STORAGE 'Y' TIMES RUNOFF COEFFICIENT 'PHI'



STEP 3

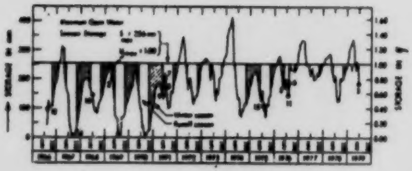
OBSERVE

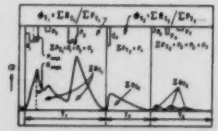
1. EQUATIONAL FORM OF THE RELATIONSHIP IS AUTOCATALYTIC WHEN VIEWED FROM LOW TO HIGH STORAGE. AUTOCATALYTIC GROWTH IS ALSO REFERRED TO AS LOGISTIC GROWTH CURVE.
2. GROWTH IN EFFECTIVE DRAINAGE OVER THE RANGE OF BASIN STORAGES TAKES AN AUTOCATALYTIC FORM.
3. THE ASYMPTOTIC RELATIONSHIP OF THE BOUNDARY CONDITIONS (UPPER AND LOWER STORAGE LIMITS) ARE OPEN ENDED.

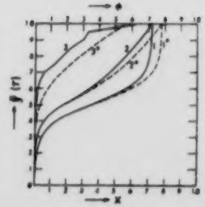
BASIN STORAGE VS EFFECTIVE DRAINAGE

'SED' MODELLING

METHODS TO OBTAIN THE 'SED' RELATIONSHIP







METHOD 1

USE A BASIN WATER BALANCE.
FROM A BASIN WATER BALANCE PLOT IDENTIFY INDIVIDUAL STORM'S RUNOFF VOLUMES AT CORRESPONDING STORAGE CONDITIONS. LET THE MAXIMUM STORAGE AMPLITUDE REPRESENT THE RANGE OF STORAGE CHANGE IN THE BASIN.

METHOD 2

USE SEASONALLY LUMPED INPUT AND OUTPUTS.
FROM THESE RUNOFF COEFFICIENTS ASSUMING THE STORAGE EFFECTIVE RUNOFF RELATIONSHIP MUST PASS THROUGH THE MEAN, MAXIMUM AND MINIMUM OF THESE POINTS. FORCE A SED RELATIONSHIP THAT FITS ALL POINTS.

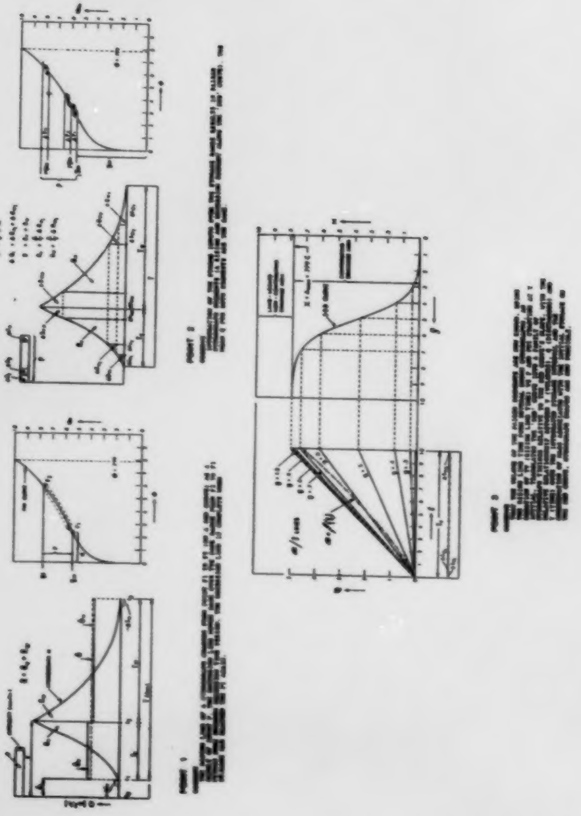
METHOD 3

USE FLOW DURATION CURVES.
A SMOOTH PLOT OF THE FLOW DURATION CURVE REPRESENTS THE RANGE OF STORAGE STATES. THE DERIVATIVE OF THIS RELATIONSHIP YIELDS.
STORAGE VS 'PHI' RELATIONSHIP, FROM WHICH THE 'SED' RELATIONSHIP CAN BE DETERMINED.

BASIN STORAGE VS EFFECTIVE DRAINAGE

'SED' MODELLING

DEVELOPING HYDROGRAPH SHAPES FROM THE 'SED' CURVE

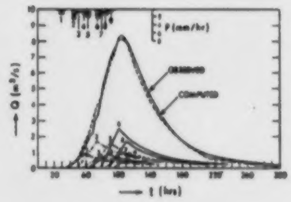


THE SED MODEL (4 OF 4)

BASIN STORAGE VS EFFECTIVE DRAINAGE

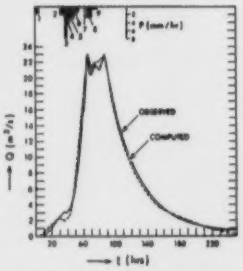
'SED' MODELLING

HYDROGRAPH RESULTS FROM 'SED' MODELLING



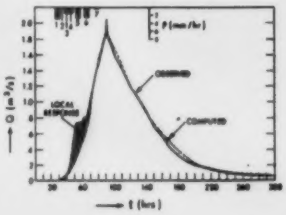
EXAMPLE 1

INITIAL STORAGE = 0.394
TOTAL PRECIPITATION = 63.700 MM
EFFECTIVE DRAINAGE = 22.200 MM



EXAMPLE 2

INITIAL STORAGE = 0.697
TOTAL PRECIPITATION = 106.000 MM
EFFECTIVE DRAINAGE = 53.200 MM



EXAMPLE 3

INITIAL STORAGE = 0.429
TOTAL PRECIPITATION = 69.400 MM
EFFECTIVE DRAINAGE = 5.700 MM

CANADIAN HYDROLOGY SYMPOSIUM (CHS:88)
ASSOCIATE COMMITTEE ON HYDROLOGY
NATIONAL RESEARCH COUNCIL OF CANADA
MAY 9-11, 1988
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SYMPOSIUM CANADIEN D'HYDROLOGIE (SCH:88)
COMITÉ ASSOCIÉ D'HYDROLOGIE
CONSEIL NATIONAL DE RECHERCHES CANADA
LES 9-11 MAI 1988
BANFF, ALBERTA

Forested watershed studies in the southern interior of British Columbia: reflections and projections

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ABSTRACT In the southern interior of British Columbia, many watersheds that supply water for domestic use or irrigation also have important forest resources. Management of watersheds for both water and trees often leads to concerns by the public and resource managers over the hydrological effects of forestry activities and a demand for local information on these effects. A number of watershed studies have been carried out in response to this demand. Early studies in the 1960's using existing streamflow data from logged and unlogged watersheds were not too successful. In the 1970's, a one-year study of logging impacts on water quality and a multi-year paired watershed study of the effects of a wildfire on streamflow provided some of the first local data for the southern interior. Efforts to develop a study of logging impacts on summer low flows in the Okanagan Basin were unsuccessful, mainly due to a lack of suitable watersheds. In 1982, a long-term paired watershed study was started in the Okanagan Basin. These various studies are reviewed and the future role of the experimental watershed approach in forest hydrology research is discussed.

RÉSUMÉ Dans la partie méridionale de l'intérieur de la Colombie- Britannique, plusieurs bassins versants qui fournissent de l'eau pour fins domestiques et d'irrigation supportent aussi une ressource forestière importante. La gestion des bassins pour ces deux ressources provoque souvent, chez le public ainsi que les gestionnaires, certaines inquiétudes à propos des effets hydrologiques des activités forestiers. La demande d'information locale sur ces effets a entraînée l'exécution de plusieurs études. Les prèmieres études, dans les années 60, basées sur des données hydrométriques déjà existantes en provenance de bassins exploités et non-exploités, furent en échec. Les premières données au niveau local pour la région méridionale de l'intérieur de la Colombie-Britannique furent obtenues dans les années 70 suite à une étude d'une année à propos des influences de l'exploitation forestière sur la qualité de l'eau, ainsi qu'une étude pluri-annuelle en bassins jumelés sur les conséquences d'un incendie forestier sur l'écoulement. Les tentatives déployés pour développer une étude sur les effets de l'exploitation forestière sur les débits d'étiage de la saison estivale dans le bassin de l'Okanagan n'ont pas aboutis en raison de la difficulté de trouver les bassins convenables. En 1982, une étude à long terme de bassins jumelés fut démarrée dans ce même bassin. Cet article rend compte de ces différentes études et discute du rôle futur des bassins expérimentaux dans la recherche en hydrologie forestière.

INTRODUCTION

In the southern interior of British Columbia (B.C.), many communities and individuals depend on small forested watersheds for domestic and irrigation water supplies. In addition, the merchantable timber in these watersheds is needed to support a viable forest industry. In the low-elevation dry-belt valley of the Okanagan Basin (Fig.1), water is particularly highly valued for recreation, irrigation, and community supply. This water comes from snowpacks in the forested highlands of the Basin which contain numerous small streams and in which logging has been extensive. Because examples of poorly planned and executed logging operations that have obviously caused detrimental impacts on streamflow characteristics (quantity, quality and timing) do exist, logging activities in forested watersheds have often been blamed for erosion, floods, and water shortage problems encountered by the water users. Strong objections to timber harvesting plans are often raised unless an analysis of risk based on local research results indicates that potential impacts will be minimal. Thus, the public as well as forest and water managers in the southern interior of B.C. have repeatedly called for local watershed studies to evaluate the hydrological effects of forestry practices. This genuine desire for studies guarantees practical application of research results.

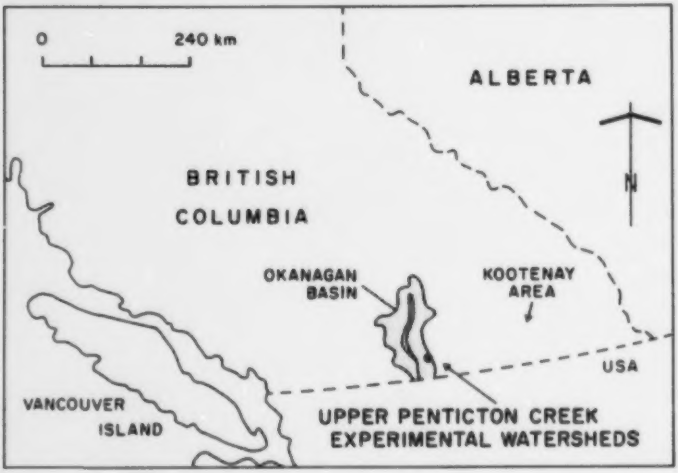

FIG.1 Location map of southern British Columbia.

This paper, (1) reviews the efforts that have gone into addressing this need since the early 1960's, (2) describes an experimental watershed study in progress (the upper Penticton Creek Experimental Watershed Study), and (3) discusses the future role of the experimental watershed approach in forest hydrology research.

HISTORICAL RESEARCH

Early studies

Attempts to assess the hydrological effects of logging in the southern interior of B.C. began in the mid-1960's (Jeffrey, 1968). However, these early efforts to establish paired watershed studies were not successful. A comparison of hydrometric data for one pair of adjacent watersheds (Windermere and Sinclair creeks) in the East Kootenays (Fig.1) revealed a poor correlation in the streamflow relationship which was attributed to differences in soil depths and the influence of limestone and sinkholes (Golding, 1968). The first formal study of logging impacts on water yield and quality in the Okanagan Basin was initiated in 1965 with an analysis of streamflow and logging data from the Esperon and Terrace Creek watersheds (Golding, 1968). This study, which was part of the International Hydrological Decade program, was not completed due to departure of the principal investigator and failure to obtain postponement of logging in the watersheds to allow for an adequate calibration period.

Okanagan Low Flow Study

Implementation of the B.C. Forest Service (BCFS) Resource Folio system in the 1970's resulted in a need for hydrological input from the Ministry of Environment (MOE) to this planning process. A subsequent desire on the part of water managers for locally derived research results on logging impacts on streams led to a serious 3-year attempt (1975-1978) to develop appropriate research strategies for the Okanagan Basin. The focus was on evaluation of potential impacts of forest harvesting and slash burning on late summer low flows in small high-elevation streams. Several options were considered by the study team, comprised of hydrologists, professional and technical staff from the BCFS, MOE and the Canadian Forestry Service (CFS).

Because of a need for "immediate" answers, a short-term synoptic approach, which was being applied in Alberta (Swanson & Hillman, 1977), was evaluated. The concept was to monitor streamflow in a number of logged and unlogged watersheds over a period of 1 or 2 years and statistically compare differences in flows between the two types of watershed. Analysis of existing flow data indicated that an inordinately large number of watersheds would be required to detect even a 100% change in low flows with only 80% probability. This approach was not considered further.

The second proposal considered was a combination of short- and long-term paired watershed studies. Two pairs of logged and unlogged watersheds would be monitored for 2 years to give a quick indication of harvesting effects on low flows, while a traditional long-term paired watershed study would be concurrently established. A screening of potential watersheds through extensive field and office assessments revealed the surprising finding that few suitable watersheds could be located. In fact, only two pairs of watersheds appeared promising. A moratorium on logging one of these pairs (located in the upper Trout Creek basin) was obtained and a hydrogeological study plus an intensive short-term streamflow and water quality monitoring program were carried out. These investigations revealed the probable existence of groundwater leakage into and out of the two drainage basins. In addition, the forest cover on the watersheds was being threatened by a nearby mountain pine beetle infestation. Thus, despite considerable effort and cooperation among the agencies, attempts to locate small watersheds suitable for studies of logging impacts on low flows were unsuccessful.

One positive result of these investigations was incorporation of 39 of the assessed streams into a province-wide low flow monitoring program during the summer of 1977. This program provided a regional sampling of low flow characteristics of operational use to water managers and of potential value for future low flow-logging impact assessments. These data were evaluated by Cheng *et al.* (1982) and have given a new awareness of the wide variability in flow characteristics in a relatively small and supposedly "hydrologically homogeneous" region.

Other watershed studies

A short-term paired watershed study of the effects of logging on the quality of water in Dennis Creek, a high-elevation tributary of Penticton Creek in the Okanagan Basin, was conducted in 1973 (Hetherington, 1976). This study was instigated by a forest company, Northwood Properties, and was carried out in cooperation with the CFS and the federal Water Quality Branch. It reflected a concern by the company and the public over logging impacts on water quality in a watershed that supplied water for the City of Penticton. The approach taken was to monitor water quality above and below the logged area in Dennis Creek and in an adjacent unlogged drainage. The sampling program was designed and coordinated by the CFS but the water samples were collected by company personnel. This procedure worked very well, particularly as the company was interested in the results and conscientious in discharging their responsibilities. The findings were in general agreement with control watershed studies elsewhere.

A severe forest fire (the Eden fire) in 1973, which burned over 60% of a gauged watershed (Palmer Creek) just north of the Okanagan Basin, presented an opportunity for an "unplanned" paired watershed study. the MOE recognized this opportunity and developed a modest study. A reasonably good pre-burn correlation was obtained for seasonal and monthly runoff between data from the 18-km^2 Palmer Creek watershed and the nearby 143-km^2 upper Salmon River drainage. New gauging stations were established on Palmer Creek, to obtain better post-burn flow data, and in the adjacent 8 km^2 Kernaghan Creek watershed, which served as another control. Results for the first 4 post-burn years indicated a general trend to higher April-August and August-November runoff plus higher and earlier spring peaks (Cheng, 1980). Mass soil movements also increased in the burned watershed. Despite limitations of the data and a lack of rigorous statistical significance for some of the variables, the results agreed with those from better controlled studies elsewhere. The important point of this exercise was that it provided valuable "local" data which has been integrated into the forested land and water management decision making process.

THE UPPER PENTICTON CREEK EXPERIMENTAL WATERSHED STUDY

In 1982, a long-term experimental watershed study was established in three small (approximately 4.5 km^2 each) tributary watersheds in the Upper Penticton Creek watershed (Fig. 1). This occurred in response to increased public demand, political pressure, and the concerted efforts of management, operational, and research personnel from various government agencies. The project was initiated by the BCFS with support from the Air Studies and Water Management Branches of the MOE and the Water Survey of Canada and input from the CFS and the Forestry Faculty at the University of B.C. The main objectives of the Upper Penticton Creek Experimental Watershed Study (UPCEWS) are: (1) to obtain a better understanding of hydrological processes and relationships operating in Okanagan Basin high elevation forested areas, (2) to evaluate changes in hydrological variables, particularly streamflow, as a result of logging and other forestry activities, and (3) to develop land management guidelines and prescriptions for safeguarding water resource values.

The intent of the study is to monitor the three selected watersheds (240, 241 and Dennis Creeks) for a period of 10-15 years, including 5-7 years for calibration and 5-8 years for post-logging assessment. One of the three gauged watersheds will be logged commercially while the second one will be logged according to prescriptions designed for specific watershed management goals. Changes in streamflow from the treated watersheds will be evaluated using data from the unlogged control watershed. The main study is limited in scope, including only the basic measurements of streamflow, precipitation (rain and snow) and air temperature. However, provision is made for inclusion of studies on hydrological and ecological processes and mechanisms both within and adjacent to the study area. Ecosystem classification maps have been produced for the three study watersheds (Smith, 1984). Other studies underway or to be initiated include investigations of water quality and nutrient budgets, streamflow generation mechanisms, and snow accumulation and ablation. These companion studies will help explain hydrological and ecological changes that occur as a result of forestry activities.

The results of preliminary 4-year analyses of annual water yield and water quality relationships between 240 and 241 Creeks show that good correlations exist between these two watersheds. These results suggest that the objectives of the study are feasible. The calibration period will be continued for another 2 to 3 years to allow for completion of several companion studies and to establish reliable calibration relationships for streamflow and water quality variables.

Study results will be used to help solve land use conflict problems and to develop forest practice guidelines for improved watershed management. They will be disseminated to agencies involved with the stewardship of forested watersheds and to those responsible for flood control and water management works. Special efforts will be made through seminars, workshops, training sessions and public meetings to ensure effective transfer of knowledge and technology derived from this study.

DISCUSSION

Experimental watersheds have often been used as outdoor laboratories to study hydrological processes and their changes resulting from natural or man-induced disturbance such as extreme storm events, cover alteration and road construction. The pros and cons of using the experimental watershed approach have often been the subject of debate (Ackermann 1966, Renne 1967, Hewlett et al., 1969). However, critics of experimental watersheds generally agree on their necessity despite alleged disadvantages such as leakage, unrepresentativeness , high costs, and difficulties in transposing results. Ward (1971) has concluded that none of the supplementary approaches, such as plot studies or models, is a replacement for the experimental watershed approach because, ultimately, results from all other methods must be verified and assessed in relation to watershed data. Nevertheless, the desirability of using the experimental watershed approach can be appropriately determined only if each specific case is assessed on the basis of its capability, in comparison to those of alternative methods, of achieving study objectives formulated to solve scientific and/or management problems.

When the UPCEWS project was established, two of the major forested watershed studies in western Canada, Marmot and Carnation Creek, were supposedly drawing to a close. It was a response to a demonstrated need for information to improve watershed management in the southern interior of B.C., a region with pressing water supply problems. The experimental watershed approach was chosen because of the lack of suitable alternative methods capable of demonstrating the hydrological effects of forestry practices on land units similar in size to many water supply basins. The application of results from watershed experiments conducted elsewhere or from computer simulation models not verified by local data always presents a credibility problem with the users and managers of forest and water resources.

In British Columbia, forest land management planning is evolving toward the use of natural drainage basins or their tributary watersheds as basic units. One example is the recent adoption by the ministries of Forests & Lands and Environment & Parks of a policy to prepare integrated watershed management plans for designated water supply watersheds. The average size of watershed used for community and irrigation water supplies in southern of B.C. is about 100-500 ha (Cheng *et al.*, 1988). Therefore, results from experimental watershed studies such as the UPCEWS project would have more direct application than data from plot studies, indoor laboratories, or computer simulation models.

The transferability of experimental results is essentially governed by the similarity in size and hydrological conditions between the study watersheds and those areas to which the results are to be applied. It also depends on how results are applied and what degree of confidence is required. The study watersheds of UPCEWS are in the Engelmann Spruce/Subalpine Fir biogeoclimatic zone which is representative of the most productive timber and water supply areas in the southern interior of B.C. The ecological classification work currently being done in B.C. will be useful in determining the transferability of study results from these experimental watersheds. The preliminary good correlation for streamflow between the two study watersheds of the UPCEWS project indicates that any groundwater leakage is probably insignificant, relatively constant and not a problem for interpreting study results.

It is difficult to evaluate the costs of the UPCEWS project relative to the use of other methods due to differences in usefulness and user acceptability of the results generated. However, this study can be expected to provide a better understanding of forest-water interactions in the high elevation areas of the Okanagan Basin and the southern interior of B.C. This will permit improved planning of forestry activities and avoid unjustified operational delays and unnecessary withdrawals of forested lands from allowable annual cuts. As well, more reliable estimates of peak flows for designing logging road culverts and drainage facilities will be possible with data from the study. This will result in cost savings resulting from reduced transportation interruptions and repairs associated with logging road failures.

PROJECTIONS

The future role of the experimental watershed approach in land use hydrology studies in B.C. may be assessed in terms of changing patterns and emphasis in forest and land management activities. For example, the continuous expansion of forest harvesting into more difficult terrain has the potential for causing acute hydrological problems that will require information generated from watershed studies. As well, the forest renewal program currently being implemented by the BCFS and the CFS will involve increasing use of herbicides and fertilizers to ensure the satisfactory restocking of logged areas. This has the potential for detrimentally impacting water resources and increases the need for ecosystem and nutrient budget studies for which experimental watersheds are a useful approach.

Future use of experimental watersheds in interior B.C. will depend on the priorities given to research in land management and environmental protection. Judging from past experience, the use of watershed studies will probably be limited. The need for studies will have to be clearly demonstrated and they will require an integrated approach involving several agencies. In-depth watershed studies should be supplemented with less intensive, smaller-scale monitoring at a number of other locations to facilitate transposing of results. Experimental watershed studies can be even more useful if they can be incorporated into a well designed hydrometeorological network and complemented by the use of computer simulation models and analyses of data from larger watersheds. Simulation models require testing with local data to properly evaluate their applicability to a given region. Moreover, to facilitate effective transfer of study results, efforts should also be made to define regions of hydrological similarity.

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The Haney watershed study - British Columbia

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ABSTRACT Concern about the possible effects of forest harvesting practices on stream water quality in coastal British Columbia led to the establishment in 1970 of a research program using three instrumented watersheds to assess the effects of clear-cutting and slash burning operations on water quality. The watersheds lie in the University of B.C. Research Forest near Haney in southwestern British Columbia. Two more instrumented and three uninstrumented watersheds have been added to the study, which has expanded in scope to consider the effects of herbicide application and herbicide application followed by burning (browning and burning) on stream water quality as well as the effects of these operations and clearcutting and slash burning on soils and vegetation. The watersheds have also been used (a) for studies assessing some of the factors controlling stream water chemistry, and (b) to develop nutrient budgets for managed forests. The study has encountered no insurmountable problems, but the major difficulty encountered has been to ensure that uniformly high quality data are generated. The major accomplishment of the study has been the generation of probably the longest essentially continuous set of precipitation and stream water chemistry data in British Columbia, which has been of interest from the acid rain perspective as the precipitation is relatively acidic. Of the study results which have been published, the most widely used are those on the ecological impacts of slash burning which have been used to assist the development of slash burning guidelines in British Columbia's Vancouver Forest Region. Most of the study results have been used in the training of forestry undergraduate students at the University of B.C.

RÉSUMÉ En 1970, un programme de recherche fut mis sur pied suite à des interrogations sur l'impact des coupes forestières sur la qualité de l'eau dans la zone côtière de la Colombie Britannique. Le programme était centré sur trois bassins instrumentés, situés dans la forêt expérimentale de l'Université de la Colombie Britannique, près de Haney, dans le sud-ouest de la Colombie Britannique, où l'on devait étudier l'effet de la coupe à blanc et du brûlage des déchets de coupe sur la qualité de l'eau. Deux autres bassins instrumentés, et trois non-instrumentés ont été ajoutés au programme depuis, avec l'inclusion de l'arrosage à l'herbicide, et de l'arrosage suivi du brûlage de la végétation morte comme traitements, de même que l'effet de tous les traitements sur les sols et la végétation. Les bassins ont été aussi utilisés pour a) l'étude des paramètres qui contrôlent les propriétés chimiques de l'eau, et b) le développement de bilans nutritifs pour les forêts sous aménagement. Aucun problème insurmontable ne s'est présenté, la plus grosse difficulté ayant été d'assurer un haut standard de qualité dans les données récoltées. La réussite la plus notable aura été la production du plus long enregistrement continu de la qualité chimique de la précipitation et des débits en Colombie Britannique, données d'autant plus intéressantes de par l'acidité de la précipitation. Parmi les résultats publiés, les plus utilisés sont ceux se rapportant aux impacts écologiques du brûlage des déchets de

coupe, ayant servi dans l'élaboration des lignes directrices pour le brûlage des déchets de coupe dans la région de "Vancouver Forest". La plupart des résultats ont été utilisés dans la formations des forestiers à l'Université de la Colombie Britannique.

INTRODUCTION

Around 1970 (as well as today) there was considerable debate about the effects of clear-cutting and slash burning on long term forest productivity and on stream water quality. The Hubbard Brook study (Likens et *al.*, 1970) had indicated that forest removal might cause a relatively large loss of nutrients from land to stream which could significantly affect both forest productivity and stream water quality. The nitrate levels in the stream draining the cut and herbicided watershed of Hubbard Brook had exceeded U.S. permissible drinking water levels for many months - substantial periods of time. Closer to B.C., Fredriksen (1970) had reported that clear-cutting and slash burning in Oregon had significantly altered stream chemistry, with both NH_4 and Mn concentrations in stream water exceeding maximum permissible levels after slash burning. These studies, together with other primarily U.S. ones, had been used to provide data in the debate about the ecological effects of clear-cutting and slash burning in B.C. No local data were available however.

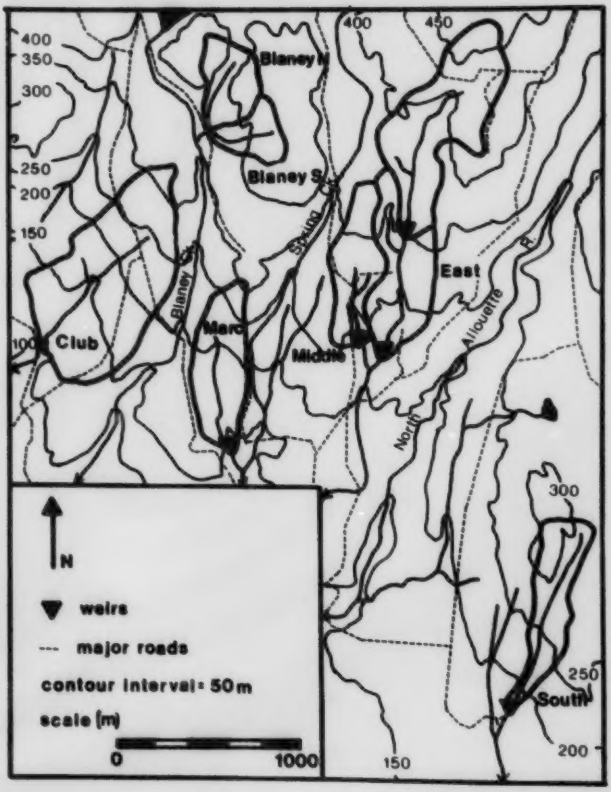
The existence of the debate, the importance of the issues to be resolved, and the absence of local data were the major driving factors behind the initial establishment of a study investigating the effects of clear-cutting and slash burning on forest productivity and stream water quality.

This initial study had four main objectives:

- To determine the chemical behaviour of small streams flowing through relatively undisturbed forested watersheds in southwestern B.C.
- To determine how this behaviour was affected by clear-cutting or slash burning.
- To explain any changes in behaviour caused by clear-cutting or slash burning.
- To provide the basis for later assessment of the influence on forest productivity of any nutrient losses caused by clear-cutting and slash burning.

As the study was originally designed to provide for my doctoral research, the first three objectives were to be accomplished during the course of my doctoral work whereas the fourth was a longer term objective to be accomplished some unspecified time in the future.

Having decided what to study, the next question to address was - how to study it. In this respect, inspiration again came from the Hubbard Brook workers. Bormann & Likens (1967) had proposed that for studies of nutrient cycling within forests it was conceptually and logistically useful to study small watersheds. Nutrient input - output budgets could be quantified, given certain assumptions about the impermeability of the underlying geologic substrate, and the use of watersheds allowed for experimental manipulation (clear-cutting and slash burning) of entire forest - stream ecosystems, which was a powerful analytical approach. Although it was decided to use a small experimental watershed approach for the study, it was felt that a knowledge of chemical processes elsewhere in the watershed was necessary if stream chemical behaviour was to be explained. Thus, right from the start and to this day, our watershed research has focused on terrestrial ecosystem processes as well as stream behaviour, in attempts to link the two.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Spring
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Marc
Middle
East
North Alouette R.
300
250
South
200
150
N
weirs
major roads
contour interval: 50 m
scale (m)
0
1000

FIG.1 Layout in the University of British Columbia Malcolm Knapp Research Forest of the experimental watersheds used the Haney watershed study.

The final question to address before the study began, was - where to conduct it. In this respect, the study location had to meet the following criteria:

- The area had to lie within the Coastal Western Hemlock biogeoclimatic zone of B.C. (Krajina, 1969). This was the region in coastal B.C. where most timber harvesting was, and still is, occurring and where water quality concerns were greatest.
- The area had to have relatively impermeable bedrock and well defined topographic watershed boundaries.
- The area had to contain three nearby and similar forested watershed, two of which could be harvested within 2-3 years.
- The area had to provide reasonable security for research equipment and installations.
- Access had to be good throughout the year.
- The managers of the area had to be able to consider research needs.

With these criteria in mind, several possible locations in the lower Fraser valley area of B.C. were investigated. One location easily topped the list for most of the criteria - this was the University of B.C. Research Forest at Haney (now the University of B.C. Malcolm Knapp Research Forest), approximately 40 km east of Vancouver. Within this Research Forest, study watersheds were delineated, concrete weirs constructed, instrumentation installed, and data collection begun. Stream and precipitation chemistry data collection begun. Stream and precipitation chemistry data collection began in September 1971. These measurements have continued to the present with only one major interruption (July 1978 - June 1979) when monitoring of streamflow and ecosystem solution chemistry was spasmodic.

HISTORICAL DEVELOPMENT OF THE STUDY

The study initially started as one graduate student's research on the effects of clear-cutting and slash burning on nutrient fluxes through forested watersheds. Weirs were constructed on the streams draining two small watersheds. The larger watershed was split into upper and lower sections by constructing another weir on the stream upstream from the first one. Thus, data were collected from three drainage areas - a small entire watershed (Marc) and the lower and upper sections of a second (East) watershed. From this 3 weirs and 2 watersheds used by one graduate student, the study has expanded to include 5 weirs and 7 watersheds used for research by approximately 35 research scientists, technicians and graduate students, and for educational purposes by numerous undergraduate students. Layout of the watersheds used in the study is given in Fig.1 and a brief description of their characteristics is given in Table 1.

The original study gave rise to several problems and questions. These were:

- How significant were losses of nutrients to stream water compared to losses to the atmosphere in slash burning operations?
- To quantify losses of nutrients from soil to stream it is necessary to quantify the factors controlling stream chemistry.
- What are the ecosystem - specific effects of slash burning on soil fertility, plant succession, and tree growth?
- How do other streams respond when subjected to clear-cutting and slash burning?

- What are the effects of other forest disturbances on soil water and stream water quality?

All past and current research in the watersheds has addressed one or more of these problems or questions. The various studies which have been and are being conducted in the watersheds are listed in Table 2, along with their locations, when they were conducted, and selected references.

It can be seen that the three main fields of emphasis in the studies are (a) stream water physical and chemical properties, (b) ecological effects of clear-cutting and slash burning, and (c) effects of forestry operations on ecosystem nutrient cycling. This emphasis is a result of several factors, primarily:

- The belief that the major impacts of forestry operations in coastal B.C. are likely to be on water quality and not on water quantity parameters.

TABLE 1 Some characteristics of the Haney watersheds as of April 1988.

*Watershed forest**	*Area*	*Elevation (m)*		*Drainage Density*	*Mature*
	(ha)	*Min.*	*Max.*	*(m/ha)*	*(% of watershed area)*
Marc	*23*	*145*	*310*	*41*	*0*
East-upper	*44*	*285*	*447*	*30*	*93*
East-entire	*68*	*215*	*447*	*41*	*60*
Middle	*19*	*223*	*315*	*54*	*0*
South	*17*	*174*	*319*	*62*	*100*
Club	*68*	*100*	*330*	*29*	*66*
Blaney-N	*13*	*312*	*375*	*29*	*0*
Blaney-S	*10*	*312*	*382*	*50*	*5*

- Stream water biological quality has been little investigated because fish values in the study watersheds are relatively low.

It was considered desirable to link the terrestrial to the aquatic components of a watershed, unlike many studies which investigate one or the other. It was believed early in the study that a knowledge of the processes occurring in one component of the watershed could help to explain the processes occurring in the other component.

There has been a considerable focus on nutrients because ecosystem nutrient status is considered to be one of the major determinants of forest productivity in coastal B.C.

TABLE 2 Summary of research carried out in the Haney watersheds.

Project No.	Project Title	Watersheds studied	Duration of study	References
1.	*Leaching losses vs. losses to the atmosphere*			
1.1	*Effects of slash burning on nutrient fluxes to stream water and to the stream water and to the atmosphere.*	*East, Middle*	*1971-present*	*Feller & Kimmins 1984*
1.2	*Development of models to predict nutrient loss to the atmosphere from from slash burns in Coastal B.C.*	*East, Middle elsewhere in UBCRF[1] + GVWD[2]*	*1970-present*	*Feller et al 1983*
2.	*Factors controlling stream chemistry*			
2.1	*Influence of stream sediment on stream water chemistry*	*East, Middle*	*1980-87*	
2.2	*Relationships between periphyton and stream water chemistry*	*East, Marc*	*1980-84*	*Perrin 1982*
2.3	*Relationships between climate, soil solution chemistry, precipitation chemistry, plant nutrient uptake,*	*Club, East, Marc, Middle, South*	*1971-present*	*Binkley et al 1982* *Feller 1977, 1987* *Feller & Kimmins 1984*
3.	*Effects of slash burning on soil fertility and vegetation*			
3.1	*Effects of slash burning on soil fertility, plant succession, and Douglas-fir growth in the coastal Western Hemlock zone of B.C.*	*East, Middle elsewhere in UBCRD + GVWD*	*1980-present*	*Feller 1988*
4.	*Response of different streams to clear-cutting and slash burning*			
4.1	*Effects of clearcutting and slash-burning in southwestern B.C. on stream water physical and chemical properties*	*East, Middle, South, elsewhere in GVWD*	*1971-present*	*Feller 1979, Feller & Kimmins 1984*
4.2	*Effects of clearcutting and slash-burning on dissolved oxygen levels in small streams in southwestern B.C.*	*East, Marc, Middle, Blaney N + S*	*1971-present*	
5.	*Effects of other forest disturbances on soil water and stream water quality*			
5.1	*Effects of herbicide application on soil water and stream water chemistry*	*Club, Marc*	*1979-1987*	*Bigley & Kimmins 1983*
5.2	*Effects on stream water quality of herbicide application followed by prescribed fire*	*Marc*	*1987-present*	

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[1] *U.B.C.R.F. – UBC Research forest at Haney.*

[2] *G.V.W.D. – Greater Vancouver Water District.*

PROBLEMS ENCOUNTERED IN THE STUDY

No insurmountable problems have been encountered during the course of the study. No attempt has been made to turn the study into a high profile one such as the Carnation Creek study in B.C. so the study has been able to continue on a minimum of funding. There are always difficulties obtaining funds from research granting agencies, such as NSERC, for long term studies which do not offer many publications in a short time period. This has been overcome by opportunistically making use of whatever funds have been available, such as from Federal government make-work projects.

The security and assistance provided by the U.B.C. Research Forest has resulted in few maintenance or vandalism problems and relatively few missing data. The mild climate and regular weekly visits to the study watersheds have also contributed to the relative lack of missing data. With regard to streamflow, the number of days of missing data from 56 1/2 weir-years (1 weir year = one weir operating for one water year) has been 510 (approximately 2.5% of the total time) except for one 11 month period from July 1978 until June 1979 when, due to limited funding, data were infrequently collected.

If one difficulty must be singled out as being the most significant, it has been to ensure that uniformly high quality data are generated. A turnover of graduate students and technicians has resulted in little continuity over time. Each new person must be trained and, as human biases influence data collection, some inconsistencies have inevitably crept into the data generated by the study. Most, if not all, of these inconsistencies have been eliminated but this has involved considerable effort and has resulted in reduced sample replication as some data have had to be excluded.

Another influence on data quality has been the instrumentation used. Some instruments, such as our Radiometer conductivity meter, and Varian AA5 atomic absorption spectrophotometer, have been incredibly reliable and are still working as well today as they were 17 years ago when the study commenced. Other instruments have caused significant problems. Our Technicon Autoanalyser had been very reliable although its operators were not always as familiar with chemistry as they might have been. This instrument was replaced with a Dionex 2110i ion chromatograph which was so unreliable and expensive and came with such bad service that I would not again contemplate automated ion chromatography as an analytical method, and have switched back to colorimetry. During the period we had the ion chromatograph the delay in analyzing our samples increased to the point (up to 15 months) where the results of the analyses may be suspect.

One difficulty we encountered early in the study was how to assess the significance of the effects of forest treatments on stream water quality. Unlike Hubbard Brook, where the effects of the cutting and herbicide treatment (Likens *et al.*, 1970) or just commercial clear-cutting (Pierce *et al.*, 1972) were very pronounced, the effects of different forest management practices on stream water quality at Haney are less obvious (Fig.2). It was felt that a statistical technique had to be used to determine the significance of any treatment effects and particularly, their duration. THis aspect has often been ignored by water quality studies, or has sometimes been addressed rather simplistically by comparing gross mean values calculated from time series data.

With the assistance of R. Hilborn (then from the Institute of Animal Resource Ecology, University of B.C.), a paired t-test analysis was developed. This involved for a given parameter, calculating the difference between the treated and the control stream for a number of time periods before treatment occurred and again for the same time periods after the treatment. The differences for time periods during the pretreatment period were paired with the differences for the corresponding time periods during the post-treatment

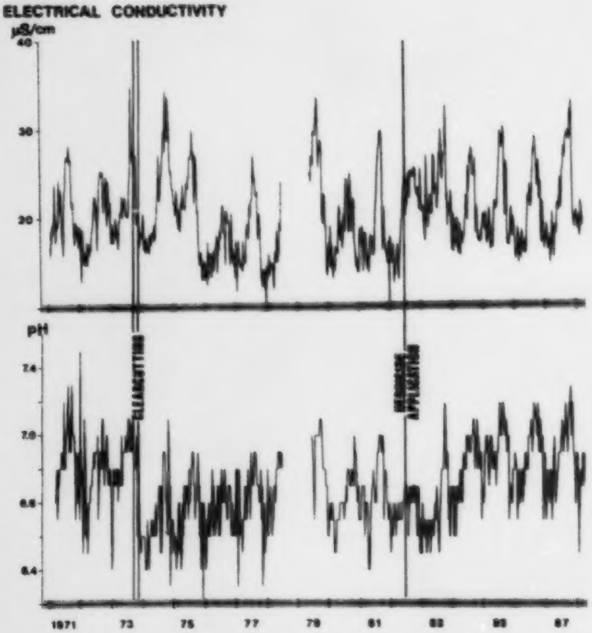

FIG.2 Temporal variation in electrical conductivity and pH of Marc stream, based on weekly measurements.

period and a paired t-test was used to test the null hypothesis that there was no difference between the average difference for the post-treatment period and that for the pretreatment period (Feller, 1979; Feller & Kimmins, 1984). This test has stood up to peer review on several occasions and Stewart-Oaten *et al.* (1986) have recently proposed a very similar test for determining the significance of the effects on aquatic organisms of a point source of pollution. Thus, there is support for the test's validity. However, if two watersheds were to respond differently to some natural change in the environment, particularly to weather, then it is conceivable that the test could find that there were significant differences in stream water parameters form one year to the next in an unperturbed watershed, as has occasionally been found at Haney (Feller & Kimmins, 1984). Thus, the power of the test is still somewhat uncertain.

MAJOR ACCOMPLISHMENTS OF THE STUDY

Probably the major accomplishment of the study has been the generation of a long, almost continuous set of precipitation and stream water chemistry data. This data set appears to be the longest, time-wise, in British Columbia, and one of the longest in Canada (Fig.2). Because the precipitation in the Haney area is quite acidic (mean annual pH = 4.5 - 4.7) the data set is of interest from the acid rain perspective (Feller, 1987).

Another major accomplishment of the study has been the use of the watersheds to study, successively, the ecological effects of different forest management practices. For example, the Marc watershed was clear-cut in 1973. It was used to study the effects of this clear-cutting on water quality, amongst other things, until 1982 when it was subjected to a herbicide application. The effects of this treatment were studied until 1987 when part of it was given another herbicide application prior to burning in late summer 1988. Thus, it is now being used to study the ecological effects of an increasingly important forest rehabilitation operation - browning and burning. This watershed, then, has been used to study three different forest management practices and has been of long term value. It is planned to use East, Middle and South Creek watersheds in a similar fashion. In contrast, a number of other watershed studies have appeared to be relatively short lived as they have been used to study one treatment only.

The third major accomplishment of the study has been its contribution towards the education of hundreds of forestry undergraduate students who, during their period of study at the University of B.C., have visited one or more of the study watersheds and have been presented some of the study's results in various lectures. Virtually all the students who have obtained an undergraduate degree in forestry at the University of B.C. during the last 5 years have been exposed to some aspects of the study. Consequently the study has had an important education role in the training of B.C.'s future foresters. It is hoped that this will lead to a more enlightened management of B.C.'s forested watersheds.

Through the provision of (a) notice boards describing the study and its results and (b) guided tours by staff of the University of B.C. Research Forest and Faculty of Forestry, numerous members of the public, school groups, and practising foresters have also been exposed to the study. Thus, the educational value of the study has not been restricted to undergraduate forestry students. This has only lead to a greater understanding by all interested groups, of the impacts of forest management practices on the physical and chemical quality of stream water in coastal B.C.

One accomplishment that should have occurred but has not, is the rapid publication of all the results and findings of the study. Only a fraction, probably less than 50%, of the findings have been published and are generally available. The unpublished findings have been used in the teaching of undergraduate forestry students and for the education of those who have visited the study watersheds, however, and attempts are being made to have them published. Of the published findings, those relating to the ecological effects of slash burning were incorporated in a review of the subject (Feller 1982) which was used as a basis for the current slash burning guidelines put out by the B.C. Forest Service for the Vancouver Forest Region (Klinka et al., 1984). These findings of the Haney watershed study are the most widely used by foresters.

Some of the techniques and methodologies used by various workers in the Haney study have been adapted or used directly elsewhere. Thus, Perrin (1982) studied relationships between periphyton and stream water N and P in the Haney streams, and subsequently studied similar relationships in lakes with fisheries researchers (Perrin *et al.*, 1984).

Having briefly discussed some of the more practical aspects of the study, it must be stated that conducting research and collecting, analyzing, and interpreting data produce personal benefits of an intellectual and skill development nature, for those people involved in the work. Even if research findings are not made generally available, the research can be valuable through its effect on the intellectual and skill development of those associated with it. In this respect, the Haney study has been of value to the approximately 35 university staff, graduate students, and technicians who have been associated with it to date.

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Jamieson Creek experimental watershed in the Greater Vancouver municipal catchments

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ABSTRACT Jamieson Creek experimental watershed was established in 1969 in response to (1) lack of knowledge of the hydrologic system in south coastal British Columbia and (2) concern for the effects of timber harvest on streamflow. An ongoing program has been carried out to satisfy the second concern. Superimposed on this have been short-term projects (mainly theses research) directed toward the first concern. The Greater Vancouver Water District practices very conservative forest management, the goal being to provide good quality water not to maximize the return from the timber resource. The effect of harvesting only 19.2% of Jamieson Creek watershed has been minimal. The main accomplishment of the research program has been to provide a training ground for students, and to significantly improve understanding of the south Coastal Mountains hydrologic system. The program will not cause any dramatic changes in forest management in British Columbia but has moved us forward in understanding the hydrologic system and its inter-relation with forest management. The research basin approach has been an appropriate one for this university - oriented research program.

RÉSUMÉ Le bassin expérimental de Jamieson Creek fut établi en 1969 en vue de répondre (1) a un manque de connaissance concernant le système hydrologique de la zone côtière du sud de la Colombie Britannique et (2) a des inquiétudes face aux effets de la coupe forestière sur les cours d'eau. Un programme a été entrepris sur une base continué afin de satisfaire au deuxième point. De plus, plusieurs projets à court terme (principalement thèses de recherche) ont contribué au premier point. Le District Hydrologique de la Cité de Vancouver pratique un aménagement forestier très conservateur dans le but de fournir une eau de bonne qualité, non pas pour maximiser la récolte forestière. La coupe de seulement 19.2% du bassin Jamieson n'a créé qu'un impact minimal. L'accomplissement majeur du programme de recherche a été de fournir un entraînement pour les étudiants, et d'améliorer significativement nos connaissances du système hydrologique des montagnes côtières du sud de la province. Le programme ne causera pas de changements dramatiques dans l'aménagement des forêts mais nous aidera a améliorer nos connaissances du système hydrologique et de son interrelation avec l'aménagement des forêts. Le bassin de recherche représente une approche appropriée pour un programme de recherche effectué par une université.

INTRODUCTION

An experimental basin is one in which natural conditions are deliberately modified and in which the effects of these modifications on the hydrologic cycle are studied. Experimental watersheds have been used in land-use hydrology research since the early 1900s and their usefulness has been debated for much of the time since then.

The premise underlying the use of small drainage basins for determining the hydrologic effect of land-use changes is that the individual basin integrates the physical and chemical forces acting upon water within its boundaries. It has proven difficult to isolate individual hydrologic phenomenon however, because the drainage basin is a complex natural unit. Hewlett *et al.* (1969) pointed out, however, that plot studies are necessary to explain watershed effects, but that the experimental watershed gives an integrated result that is most useful in providing practical guidelines for management. Even critics of experimental watersheds conclude that despite the problems they do have their place in the science of hydrology. One of the difficulties of carrying out an experimental watershed program is the long-term nature of the study. The calibration period should run long enough to develop the relationship between the hydrologic variables of interest on the two basins at a predetermined level of statistical precision. Depending on the variability between the two basin this may take up to a decade. Unless complete control over the land use of the basins is obtained by those responsible for the research there may be overwhelming pressure by the land-management agency to alter the vegetation cover of the treatment basin (e.g., timber harvest) before a satisfactory calibration has been achieved. Even more disastrous to the research objectives would be modification of the forest cover of the control basin. Also, the post-treatment period must be of sufficient length to obtain a reasonable sample size and to sample some of the more extreme annual weather conditions. The land-management agency may change the land-use prematurely, thus effectively ending the post-treatment period.

JAMIESON CREEK EXPERIMENTAL WATERSHED

Jamieson Creek experimental basin was established in 1969 as part of the watershed research program in the municipal watersheds of the Greater Vancouver Water District (GVWD). This program was in response to a general lack of knowledge of the hydrologic system in coastal British Columbia and, in particular, concern for the effects of timber harvesting on water quantity and quality in the municipal water supply area. It was expected that the results of this research program could ex extrapolated to other coastal watersheds.

Probably the single factor contributing most to criticism of experimental watersheds has been the failure to adequately define the problem in terms of scientific and management objectives, and to clearly state the objectives. Goodell (1973), the coordinator of the Jamieson basin at its beginning, defined the objectives as:

(1) to gain basic hydrologic knowledge of the south Coastal Mountains that are represented by Jamieson Creek,

(2) to quantify the effects of forest harvest and other forestry practices on the quality, quantity and temporal distribution of water yield,

(3) to derive guidelines for forestry operations such that detrimental effects will be negligible, and beneficial effects on the water resource will be maximized to the extent compatible with water quality.

This third objective could be better defined by elaborating on such words as maximize and compatible, but in general the objectives are clearly stated, thus setting the bounds on the research program.

Research approach and basin selection

In 1969, the forest hydrology research program was established on the Greater Vancouver Municipal catchments through the efforts of the late W.W. Jeffrey of the U.B.C. Faculty of Forestry. As part of this program, Jamieson Creek and Elbow Creek basins were selected as treatment and control basins, respectively.

The experimental watershed approach was chosen for a combination of reasons. This approach focuses on a particular area rather than a particular study. This promoted the use of Jamieson Creek as a site for various studies associated with hydrology. No doubt this was seen as a way of bringing into the program, in a very informal arrangement, researchers from various faculties at U.B.C. and other agencies, thus improving the probability of success of funding applications. Ongoing funding in the past 15 years has consisted of an annual grant from the GVWD, a grant which hasn't changed in size since the project beginning, but which, along with the Faculty of Forestry's provision of a full-time technician, has been the mainstay of the program. Graduate student research has been funded mainly by NSERC and Canadian Forestry Service. In the early years of the project, advice, instrument loans and financial assistance were contributed by the Meterological Service of Canada, Canada Department of Energy, Mines and Resources, and by various faculties of U.B.C. Water Survey of Canada constructed the Jamieson Creek stream gauge and supplied the water-stage recorder.

A second reason for the research basin approach was its visibility compared to other approaches, a fact that may have appealed to the chief cooperator, the GVWD. And finally, the research basin provided an "outdoor lab" for graduates and undergraduates who could build on one another's database.

Selection of the pair of research watersheds proved difficult. Concerns to be addressed were access and distance from Vancouver, degree to which the watersheds had been disturbed, tenure on the forest resource, and the physical characteristics of the watersheds. Advantages of the two basins chosen were:

(1) They were unroaded and uncut, access was possible, and they were only an hour's drive from Vancouver,
(2) they were within Greater Vancouver's municipal watershed system in which water supply, not the timber resource, was of prime concern. This meant that the value of the timber would not dictate the harvest schedule,
(3) access to the municipal watershed is not permitted to the public. This safeguards instruments and equipment.

Description of the study area

Three watersheds are managed by the GVWD for the water supply of Greater Vancouver. These comprise 61,000 ha of which 34,000 ha within the coastal biogeoclimatic zone are classified as productive and within which is Jamieson Creek basin. GVWD holds 20% of the 61,000 ha in fee simple, the remainder being held in a 999-year lease from the Province. From 1920 to 1940 on fee simple land there was railroad logging in continuous blocks along the valley bottoms. After a 20-year hiatus, logging in the form of a small-scale log salvage began in 1961 to combat a balsam woolly aphid attack that was expected to create a high fire hazard. In 1967 the GVWD was awarded a Special Tree Farm Licence. The primary object of forest management was recognized in the licence as provision of an adequate supply of high quality water to member municipalities. Since 1978, the Wyssen skyline system has been used in selected settings to reduce ground disturbance. Site preparation after logging has been confined to broadcast burning or scarification.

The pretreatment calibration period was 1972-1978. Treatment took place over seven years, 1978-1984, during which time only 19.2% of the basin had been cleared for roads and by timber harvest. The post-treatment period is only three years, 1985-present.

Basin instrumentation

There has been a wide variety of instrumentation on the basin to serve special studies. However, the ongoing instrumentation and sampling program to satisfy the basic objectives of the watershed research program are as follows:

> Precipitation: (8 storage gauges, 2 of which are in Jamieson; 5 recording gauges in Jamieson, one in Elbow; 1 snow pillow and a 10-point snow course in Jamieson).
>
> Water quality sampling: (2 rain, 2 seepage (1 in clear-cut, 1 in forest), 1 throughfall, 1 streamflow in Jamieson; 1 rain, 1 throughfall, 1 streamflow in Elbow).
>
> Streamflow: (3 m Cipoletti weir with 55 $m^3\ s^{-1}$ capacity, and a Steven's A-35 water-stage recorder with combination water-stage manometer (nitrogen gas purge system) in Jamieson; 120° V-notch weir with float-type Steven's A-35 water-stage recorder in Elbow).
>
> Air temperature: (1 recording thermograph with maximum-minimum thermometer in Jamieson and 1 in Elbow).
>
> Water temperature: (recording thermograph at Jamieson Creek weir).

RESULTS AND CURRENT RESEARCH

Many of the studies on Jamieson have been carried out for PhD (8), Masters (3) and bachelors (8) degrees.

Plamandon *et al.* (1972) assessed the hydrologic role of the forest floor by evaluating the processes controlling water absorbed during precipitation and lost during drainage, evaporation, and transpiration. Forest-floor depth could be predicted by such topographic factors as elevation, slope, latitude, and radiation. Radiation along accounted for 30% of the variation in forest floor depth because of its effect on decomposition rate. Water conductivity and retention of the forest floor is largely a function of the degree of decomposition of the organic matter.

Chamberlain (1972) traced the movement of water from the surface organic layers to the relatively impermeable layers that commonly occur where lateral flow occurs. The saturated zone above the impermeable layer had a saturated conductivity of 35 cm h^{-1}, the B horizon of 0.3-1.7 cm h^{-1}, but the whole profile could transmit water at 200 cm h^{-1}, indicating the presence of macropores and root channels between the surface organic layer and the basal soil zone. The B horizon wetted from the top down and from the bottom up; interflow occurred as saturated flow over shallow bedrock assisted by rapid transmission of water from the surface. Chamberlin's work points out how Coast Mountain forest soils quickly conduct water to streams and how inadequate in describing the system are laboratory determinations of saturated and unsaturated conductivity.

DeVries & Chow (1978) used simulated rainfall on moderately well drained soils with a 10 to 30 cm surface organic layer. Infiltration capacities were sufficiently high that at the simulated rainfall rates of 2.6 cm h^{-1} there was little overland flow, even on disturbed sites. Water percolated down through the soil till it reached the less permeable H and A_e horizons where some moved laterally until it found its way into root channel openings. Some water moved much more slowly downward through the H and A_e layers in response to the matric potential gradient. Initially, root channels provide most of the drainage, but as the soil matrix wets up percolation through the matrix increases. After the rain the root channels soon cease to contribute to drainage. Root channels most effective in draining were those located at the top of the H horizon. Forest floor disturbance by log-skidding closed off root-channel openings, reduced the rate at which water moved through the soil, reduced the height of peak streamflow and increased the time-to-peak. Tying together the work of Chamberlin and DeVries and Chow with observed channel hydrology is the study of Cheng *et al.* (1975) who dealt with storm flow generation. Stormflow was generated by rapid flow through old root channels. Ephemeral streams rose mainly through saturated return flow that developed at the foot of long steep slopes in areas of thin, less permeable soils.

O'Loughlin (1972) related the occurrence of debris slides to site characteristics. Slides usually occur on slopes where seepage occurs indicating the role of increased pore water pressure in such failures. The sliding plane is usually the unweathered basal till. The characteristics of the slides per km^2, 0.12 slides, 1,150 m^3, 1,000 tonnes, indicate the relative stability of the area compared to other mountain regions. The number of slides per unit area was eight times higher on clear-cut areas than in forest. O'Loughlin (1974) showed that roots provided significant stability to soils on steep slopes, and that tensile strength of roots decreases rapidly after the tree is cut. Morton (1975) used O'Loughlin's data and found a decrease in root cohesion with increasing depth. The shallower the soil over a potential shear plan the more important are the roots in imparting cohesion.

Cheng (1972), using tension lysimeters and a method based on Darcy's equation, evaluated drainage through the soil matrix. Both methods provided reasonable estimates of soil-water drainage. Time trends of soil-water drainage were similar to those of Jamieson Creek streamflow, indicating that climatic, topographic, geologic, and edaphic conditions favour a large, direct contribution of root-zone water to streamflow.

Beaudry & Golding (1985) reported on snowmelt runoff rates in forest and clear-cuts during rain on melting snowpacks in the transient snow zone. These events cause the major peak flows for coastal watersheds. Snowmelt runoff rates were greater from the forest than from clear-cuts when the storm began as snow and then changed to rain. The snow in the canopy melted at a rate faster than that in the clear-cut because of greater energy inputs at canopy level. Such storms occur frequently in the transient snow zone. For rain storms when there was no snow in the canopy, snowmelt runoff rates were greater from clear-cuts. Snowmelt runoff, during rain on snow, peaks several hours later from the clear-cut than from the forest, suggesting the possibility of harvesting to desynchronize snowmelt runoff from forest and from clear-cut.

Golding (1987) reported on changes in streamflow peaks during and after clear-cutting of 19.2 of Jamieson Creek basin. For the period 1978-86, winter storm peaks showed a treatment-induced increase of a maximum 13.5%, with no indication that the increases were limited to a particular storm-size class. Summer storm peaks showed no treatment-induced increase. Winter streamflow peaks were highly correlated with total snowmelt runoff from lysimeters in the forest and in the clear-cut, but less well correlated with peak snowmelt runoff rates. There was no difference in size of peak flow whether or not melt rates were greater in the forest than in the clear-cut.

Zeman (1975) did an ionic balance in which he determined input by tropospheric fallout and output by stream discharge. There were net losses to the watershed of Na, K, Ca, Mg, Si, bicarbonate, chloride, sulphate, and phosphate. Only nitrate and ammonium showed net gains to the watershed. Most of the nitrate, ammonium, sulphate and chloride in discharge water was provide by tropospheric fallout. Weathering of soil and geologic materials were major sources of Si, Ca, Mg, K. bicarbonate. Phosphate and Na were derived equally from tropospheric and terrestrial sources.

Henderson & Golding (1983) reported on a study of soil water repellency measured by the drop penetration method. There was no difference in soil water repellency between unburned clear-cuts and the uncut forest. Soil from the slash-burned sites was more frequently water repellent than soil from the forest but differences were significant only for the first two years after burning. All humus samples were severely water-repellent. Water repellency decreased with depth in samples from both the slash-burned and forest sites.

Briere (19787) developed a land-classification system for forest management in which the land and aquatic systems were integrated. Joyce (1977) reported significant correlation between Briere's landscape units and both streambank and bedload characteristics.

Current research included the ongoing assessment of the effect of forest harvest and stand re-establishment on hydrology, particulary on streamflow regime and water quality; snow-melt runoff rates in forest and clear-cut; rain and snow interception loss by the forest canopy; fog drip; and time trends of dissolved chemical concentrations in precipitation, throughfall, seepage, and streamflow.

DISCUSSION

One of the perceived advantages of Jamieson Creek as an experimental watershed was that timber harvest was not the primary land-management objective. This meant that neither the Forest Service nor a forest company would be enjoining the researchers to hurry the calibration period or to increase the fraction of the watershed to be logged. However, this advantage has turned to be a disadvantage to some degree. The GVWD's mandate is to provide a plentiful supply of good quality water. Therefore a very conservative harvesting program is practised. The GVWD has not been convinced to increase the logged area of the watershed beyond the present 19.2%, although it is of interest to determine the hydrological effects of a more severe treatment.

Funding has always been a problem. This is not uncommon among researchers but it is exacerbated on Jamieson Creek because most of the research has been done as graduate theses. There are no ongoing funds to support such research. Each project requires application for research funding to various agencies, only a very small fraction being successful. The GVWD grant and UBC's funding of a technician is just sufficient for the maintenance of the instrument networks and data abstraction.

There are three main accomplishments. The watershed research program has provided a training ground for students, both graduate and undergraduate. The first objective, to gain basic hydrologic knowledge of the south Coastal Mountains, has been satisfied to a significant extent by research into hydrologic role of the forest floor, flow paths in soil, particularly macro-channels, the relation of pore-water pressure and root strength to debris slides, soil hydrophobicity, snowmelt runoff rates in forest and clear-cut. The second objective, to quantify the effects of forest harvest on streamflow regime and water quality, has been satisfied for the four years immediately following timber harvest. The long-term effects await a longer post-treatment period. Of all the studies, the one that is likely to have the greatest impact on coastal forest management is the study showing that snowmelt runoff rates may be greater from the forest than from the clear-cut, and that a mix of forest and clear-cut may produce lower streamflow peaks than the uncut forest simply by desynchronizing flows from various parts of the watershed.

The choice of the research basin approach was appropriate, especially in view of the nature of the research organization, the university. The research basin provided a focus and an ongoing data base for short-term projects, the frequency of which depended on graduate students entering the forest hydrology program. The objective satisfied by this phase of the research was "to determine the hydrology" of the south Coastal Mountain region. The objectives dealing with the effect of forest harvesting on streamflow quality and quantity are being satisfied by the base level, ongoing project.

The results of this experimental watershed project can't be expected to impact forest management in Canada except for coastal British Columbia. Even in British Columbia the program will not cause any abrupt changes in forest management. Typically, the program has produced new insights into the coastal hydrologic system. It has moved us forward to few steps along the path of truly understanding the hydrologic system. This program, and others, will build on the accumulated knowledge.

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Carnation creek experimental watershed - reflections on 18 years of experience with a west coast fish/forestry interaction project

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ABSTRACT Carnation Creek is a small salmon stream located on Vancouver Island, British Columbia. A long-term multi-agency project was initiated in 1970 to evaluate the effects of forestry operations on the stream and its fish production and communicate results to forestry and fishery managers. Hydrology was a supportive rather than primary focus of the project. Both terrestrial and stream processes were emphasized. Objectives have been achieved despite funding shortages, changes in coordinator and research priorities, periodic lack of interest, missed opportunities, and difficult field conditions. Achievements include significant scientific findings, effective transfer of results to potential users, and a substantial influence on the resolution of fish/forestry conflicts in coastal British Columbia.

RÉSUMÉ Le ruisseau Carnation est un petit cours d'eau à saumon de l'Ile de Vancouver en Colombie-Britannique. Un projet à long-terme, regroupant plusieurs organismes, y fut mis en place en 1970. Le but de ce projet était d'évaluer les effets des opérations forestières sur la faune aquatique et de communiquer les résultats aux gestionnaires des forêts et des pêcheries. L'accent fut mis sur l'étude des processus aquatiques et terrestres, l'hydrologie ne jouant qu'un rôle de support. Les objectifs furent atteints malgré les réductions budjetaires, les changements de coordinateur et de priorité de recherche, le défaut d'intérêt périodique, les occasions manquées et les conditions de terrain difficiles. Les réalisations du projet comprennent des découvertes scientifiques d'importance, un transfert réel des résultats aux clients potentiels et une contribution notable au niveau de la résolution des conflits entre les pêcheries et la foresterie dans la région côtière de la Colombie-Britannique.

INTRODUCTION

The Carnation Creek Experimental Watershed Project was initiated in 1970 to meet a need for local information to help minimize conflicts in the management of the fisheries and forestry resources of coastal British Columbia. It was originally scheduled for completion in 1986 but has been extended to 1991 under a revised format. The primary emphasis of the project has been on fish, stream biology and channel conditions rather than on purely hydrologic concerns, although the watershed was registered under the International Hydrological Decade program.

STUDY AREA

Carnation Creek is a salmon stream that drains a 10-km^2 mountainous watershed located on the west coast of Vancouver Island, British Columbia, Canada (Fig. 1). The basin slopes are steep with shallow, highly permeable, coarse and relatively stable colluvial soils, watertight volcanic bedrock, and mature coniferous rainforest vegetation. The climate features mild, wet winters with frequent rain storms, mild summers, and annual precipitation (mostly rain) of 2100 to over 5000 mm. Runoff is rapid with measured flows ranging from 0.02 to 65 $m^3 s^{-1}$. The stream is utilized by both salmon and trout.

NATURE OF THE CARNATION CREEK PROJECT

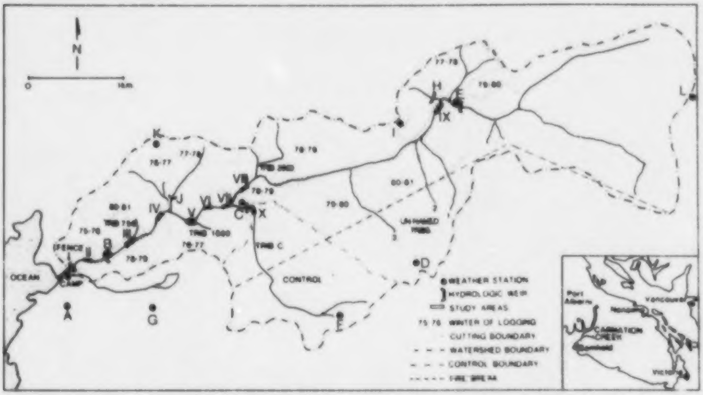
Organization

The project is multi-agency and multi-disciplinary in nature. However, it was initiated by Fisheries and Oceans Canada (DFO) and that agency provided, up to 1986, coordination and most of the funding for field operations. A Steering Committee comprised of senior representatives from DFO and other resource agencies was formed to review progress and provide appropriate direction and support. Operation of the project was supervised by a project coordinator (research scientist) assisted by a Working Group of individuals conducting component studies or lending technical or advisory support. Participating organizations included both federal and provincial fisheries, forestry and water resource agencies, universities and Macmillan Bloedel Ltd., which carried out the forestry operations. In 1986, the financial support base for coordination, field operations and data processing was broadened and the project was extended for 5 more years. A new coordinator was hired under contract for 1986 and 1987.

Study design

The original project included three phases: 5 years pre-logging calibration (1971-1975), 6 years active logging (1976-1981) and 5 years post-logging (1982-1986). A total of 41% of the watershed area was clear-cut in patches ranging from 7 to 64 ha (which merged to form a continuous clear-cut) using high-lead and grapple cable yarding techniques. Coincident with the 5-year post-logging extension (1986-1991), new logging began in the upper watershed which is not expected to affect downstream channel areas used by salmon. Silvicultural treatments included prescribed burning of slash, reforestation, some scarification, and use of herbicides. The experiment was designed to evaluate the impacts of three stream side forest management treatments: (1) a leave strip of variable width, (2) a careful treatment leaving riparian brush and avoiding channel disturbance, and (3) an intensive treatment where both sides of the stream were logged and the stream channel was disturbed by debris and yarding. Within the constraints of experimental design, normal planning procedures and logging operations were followed. However, treatments 2 and 3 are now rarely permitted in stream zones that contain salmon. An experimental herbicide treatment study, not part of the original design, took place in 1984-86 (Reynolds, 1988).

Streamflow was measured at 5 weirs and precipitation at 10 sites (Fig. 1), groundwater levels were measured at a number of locations (Hetherington, 1982,1987,1988) and two unlogged tributaries (C and E) served as hydrological controls (Fig.1). Additional facilities included a major weather station, thermographs for air and water temperatures at 15 sites, an automatic sediment sampler at B weir, a permanent fish counting fence and a permanent field camp which was staffed year-round. Hydrology concerns were addressed by DFO, Water Survey of Canada, Canadian Forestry Service, and Atmospheric Environment Service.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CONTROL BOUNDARY
FIRE BREAK
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Vancouver
Victoria
CARNATION CREEK

FIG.1 Carnation Creek experimental watershed, British Columbia.

Major week-long simulation modelling workshops (Walters, 1974) were held in 1973 and 1979 to identify research needs and ensure that adequate data were being collected. It was also hoped that these planning exercises would result in a model that would integrate results and serve as a forest management tool. A major hydrologic computer simulation, conducted by the Water Survey of Canada in 1978, helped assess the adequacy of the precipitation gauge network.

The impacts of forestry operations were evaluated by studies of both terrestrial and stream processes (Hartman, 1982; Chamberlin, 1987; Reynolds, 1988). Instream studies covered the following: fish life stages, population dynamics, and behaviour; basic stream productivity, including aquatic insects, detritus, and algae as well as fish; fish habitat, including the role of side-channels and large woody debris; changes in gravel quality, channel morphology and woody debris; suspended sediment; water temperature; water chemistry; stream discharge and possible changes after logging; and bedload movement. Terrestrial studies included the following: soil and vegetation classification; soil disturbance; revegetation patterns; landslides; hillslope and valley bottom groundwater levels; soil moisture; subsurface flow processes; precipitation interception; precipitation chemistry.

ORIGINS, NEEDS AND OBJECTIVES

The Carnation Creek Project was born out of the environmental movement of the 1960's which expressed concern about possible stream damage caused by logging operations. DFO, which has a responsibility for fish habitat protection under the federal Fisheries Act, recognized the need for "local" scientific information on the impact of forestry operations on the productive capacity of coastal salmon and trout streams. Through cooperation between its research and operations divisions, this agency had the technical and financial resources, as well as the mandate, to do something about meeting this need.

The long-term research watershed approach was chosen for several compelling reasons. In particular, the multi-year life cycle of fish dictated a multi-year in-depth investigation of a single system for adequate understanding of the processes involved. Conflicts between the fishery and forestry resources were seen to be symptoms of a lack of integrated resource management. A long-term watershed project would serve to integrate the results of short-term or single component studies and focus the expertise of the wide range of disciplines required to address the complexities of a stream-watershed ecosystem. Other factors contributing to the choice of this approach included: the variability in year-to-year weather patterns, the need for proper pre-logging background data, and the desirability of choosing the stream side management practices and cutting patterns to be evaluated.

The Carnation Creek watershed was selected after an exhaustive search on Vancouver Island. Among the important criteria were size, presence of fish, forest cover type, representative topography, accessibility, and availability. Carnation Creek was typical of the small, mountain streams utilized by representative fish species and it was close to existing logging roads. Macmillan Bloedel Ltd., which held tenure on the land, agreed to delay logging to accommodate study needs, modify logging plans and practices as required to meet study objectives, and carry out the logging and silvicultural activities as part of normal operations.

The original objectives of the project (Hartman et al., 1987) were:

(1) to develop a better understanding of undisturbed coastal rain-forest-salmon ecosystems;
(2) to explain and quantify impacts of forest management activities on stream environments and their capacity to produce salmonid fishes;
(3) to provide continuous input to the development of integrated resource management guidelines for watershed ecosystems.

An emphasis has been placed on understanding processes to maximize the transferability and application of results. Implicit in the original objectives was the goal of evaluating the rate of recovery of the stream system from any logging-related damage. This latter goal has provided the main rationale for the extension of the project.

DIFFICULTIES ENCOUNTERED

Administrative

The greatest stumbling blocks occurred on an administrative level. However, the realities of budget restraints had to be confronted on almost an annual basis. The main problems included funding shortfalls for such activities as the annual survey of channel morphology and debris and continuous staffing of the field camp. These difficulties were only overcome by strenuous efforts by committed individuals and cooperation among agencies. Even here, difficulties were encountered in finding ways to overcome administrative reluctance by one or two support agencies to provide extra funding. Some administrators simply did not view Carnation Creek as being of sufficient importance, particularly in the early years of the project. As results on logging impacts appeared, interest and at least moral support did increase among government agencies and industry in general.

Personnel limitations

The limitation in number of researchers committed to long-term involvement with the project has resulted in delays in processing, analyzing and reporting on the large data base. The lack of a full-time hydrologist assigned to oversee the hydrologic component of the project and failure to continue development of an integrative computer model are two examples. Some ancillary topics have been inadequately addressed or not covered at all, particularly on the terrestrial side (e.g. nutrient cycling, evapotranspiration, erosion). The effort required to keep the project operational in the face of funding limitations or changing research priorities also took away energies that could have been spent on research tasks. The project has had four official coordinators. This change in leadership resulted in lost time and missed opportunities in terms of maintaining momentum in achieving some of the goals and attracting additional research input and support.

Field conditions

Physical difficulties were encountered because of the relatively remote location and the climate. Heavy rains or winter snowfall occasionally blocked access to the watershed during critical periods. The harsh west coast environment, with its high frequency of heavy rain storms accompanied by high winds, flashy streamflow and high humidity, posed special problems for design and maintenance of instrumentation and equipment. Falling trees have damaged instruments and shelters resulting in lost data. Difficulties have been encountered with instream measurements of flow and other parameters because of gravel and debris movement in the channel during storm flows. The logistics of timing field visits to coincide with storm events can be formidable. In 1986, a fire destroyed part of the field camp causing restricted accommodation and losses of equipment and data.

ACCOMPLISHMENTS

Significant results

Studies have demonstrated a complex variety of both positive and negative impacts of logging on fish for different life stages, species, and time scales (Hartman et *al.*, 1987). The impacts have resulted from changes in channel morphology, channel debris volume and stability, winter stream temperatures, stream gravel quality, stream biological productivity and floodplain side-channel habitat. Changes have also been measured in streamflow, valley bottom and slope hydrological regimes, water chemistry, and incidence of small landslides and debris torrents. These data confirmed that results of hydrology studies in coastal Oregon and Washington also apply to coastal B.C. The importance of side-channels and large woody debris has been documented. Both the stream channel and fish populations remain unstable over 10 years after logging started. The long-term coho and chum salmon data base is now unique in the world, while the hydrological data base is unique for the outer west coast of B.C.

Transfer of research results

A major goal of the project has been the ongoing communication of research findings to potential users. At least 140 articles have been published in scientific journals, symposium and workshop proceedings, agency and project reports and university theses. A short film and video were also produced to explain the project. However, direct transfer by working group members at meetings or in the field has been the most effective method of communicating results to resource managers from federal and provincial government agencies and corporate sectors, professional fishery and forestry organizations, public groups and university classes. Major 3-day workshops in 1982 (Hartman, 1982) and 1987 (Chamberlin, 1987; Reynolds, 1988) provided comprehensive summaries of results that emphasized applications for management.

Impact on management of watershed resources

Carnation Creek results have been widely used in coastal British Columbia as a basis for on-site evaluations of fish/forestry interactions and for assessment and planning of forestry operations. They have served as a qualitative guide for constructive preservation of fish and their stream habitat. For example, project results were instrumental in initiating a major revision of coastal fisheries/forestry guidelines for stream protection (Anonymous, 1987) and were used to test procedures for development of a watershed forest hydrology sensitivity analysis Work Book (Wilford, 1987). The project has succeeded in heightening the sensitivity of fishery and forestry personnel to each other's resources and to hydrological concerns. Emphasis on the understanding of processes and provision of a comprehensive watershed-scale perspective of forestry operation impacts on fish and streams has been particularly valuable in this regard.

Direct use of the hydrological information has been much less dramatic or extensive. The hydrometeorological data have been used to estimate the frequency and magnitude of peak flows in other watersheds and to test and calibrate several computer hydrology simulation models. Information on the importance of subsurface flow and the effects of roads in intercepting and diverting this flow have resulted in modifications to road drainage procedures by at least one company. The impact of Carnation Creek findings on water management, however, has mostly been as a by-product of managing for fish and timber.

Researchers involved in watershed studies in the western United States from California to Alaska have shown a keen interest in the Carnation Creek project. Their advice was sought in establishing the project, they have participated in the workshops and field trips, and working group members have participated in their symposia.

HISTORICAL OVERVIEW

Value of approach taken

The Carnation Creek project has been successful in achieving its objectives for several reasons. Because of its long-term existence, Carnation Creek has become an effective agent for change and served as neutral territory for bringing fishery and forestry managers together. The project achieved credibility because of the openness and unbiased approach of the researchers in willingly sharing their information with all potential users. The local documentation of changes and impacts has given valuable support to recommendations for appropriate stream protection measures. This includes more confidence in extrapolation of results from elsewhere based on a better understanding of processes relevant to local conditions. The involvement of the forest industry in the project has resulted in greater awareness and acceptance of the Carnation Creek findings. Having a single lead agency commit substantial funding and manpower was of primary importance, although the intimate involvement of other key agencies and groups was also essential. The Working Group format fostered cooperation, closeness and a sense of commitment to the project. The permanent field camp with continuous staffing was critical to ensuring the integrity of data collection and security. The computer simulation workshops early in the life of the project, the information dissemination workshops later in the project and ongoing talks and field tours, helped focus attention, interest and support during difficult periods.

Missed opportunities and other possibilities

Some items recognized early in the life of the project were simply not pursued or could not be tackled. The 1973 simulation workshop identified an ideal project as having three components: a long-term watershed study, short-term synoptic studies in several watersheds and controlled environment studies. In particular, the synoptic approach could have evaluated a wider variety of management practices, guidelines, physiographic and climatic conditions, and facilitated extrapolation of Carnation Creek study results. However, studies using this approach have recently been initiated on Vancouver Island by DFO. A longer pre-logging calibration period would have been desirable to encompass a greater range of climatic and streamflow conditions and establish better pretreatment relationships among the various parameters. Proposed nutrient cycling studies would have provided better linkages between terrestrial and aquatic processes. Suggestions for hydrology-related studies of evapotranspiration, manipulative erosion research, snow accumulation and melt, and further development of modelling procedures were not pursued because of limitations of manpower or funding. More intensive monitoring of snow conditions was initiated in 1982 following a major rain-on-snow event that triggered a few debris torrents and small landslides, but valuable background snow data for this rare event were lacking. A greater effort might have been made in soliciting additional research input if the coordinators had not been so deeply involved in research themselves.

In recent years, the potentials for logging to increase peak flows during rain-on-snow events or accelerate the incidence of landslides have become important issues. A watershed with greater snow input and less stable soils than Carnation Creek would have been perhaps a better choice for addressing these particular problems. The stream side treatments were conducted along the same channel and resulted in cumulative and confounding downstream impacts. While these results were still very useful, single treatments on seperate channels might have better identified the impacts of each treatment. Similarly, a separate hydrological control watershed would have been desirable. However, the practicalities of finding a suitable watershed dictated the ultimate choice of options for research.

SUMMARY

The long-term Carnation Creek project has displayed remarkable resiliency in facing and overcoming numerous stumbling blocks during its 18-year history. Changes in coordinator, changing priorities of management, funding shortages, missed opportunities, periodic lack of interest, and difficult field conditions have been surmounted to achieve the original objectives. In the process, the project has played a significant role in the resolution of fish/forestry conflicts in coastal British Columbia. While not the main focus, the measurement and study of water, a significant interface between fish and forests, have played an invaluable supportive role.

ACKNOWLEDGEMENTS

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Problems of studying water balance in small high arctic basins

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ABSTRACT The extreme and persistent coldness and the prominent presence of snow pose special problems to small basin research in the High Arctic. A water balance study carried out at McMaster basin (area 33 km^2) near Resolute, N.W.T., illustrate the major difficulties and feasible approaches in investigating hydrological problems in Arctic Canada.

Water balance requires data on precipitation, evaporation, runoff and storage change on a basin scale. Precipitation is known to be notoriously under-represented and in the thawed season, the extent of the evaporating surface is continually altered by the melting snow cover. These problems can be solved by intensive snow surveys, coupled to a spatially distributed melt model, to obtain the correct information on the amount and the extent of the snow cover before and during spring. In the spring, the streams are choked by snow and ice and frequently, direct measurements of discharge are needed to obtain runoff accurately. The changing depth of the frost table governs the soil moisture storage capacity and this has to be monitored regularly in spring and summer to evaluate storage changes.

When these problems are overcome, it is possible to determine the water balance of Arctic basins correctly, the result of which is highly valuable to the inventory of Canada's northern water resources.

RÉSUMÉ Le froid extrême et persistant et la présence de neige présentent des problèmes spéciaux pour l'étude de petits bassins de l'artique. Une étude de bilan hydrique sur le bassin de McMaster (33 km^2), près de Resolute, T.N.O., illustre les difficultés et les approches possibles dans l'étude des problèmes hydrologiques dans l'artique canadien.

L'étude du bilan hydrique demande la collecte de données sur la précipitation, l'évaporation, l'écoulement et l'emmagasinement au niveau du bassin. On sait que la précipitation est sous-évaluée, et que, durant le dégel, la surface évaporante varie constamment à mesure que la neige fond. Ces problèmes peuvent être résolus au moyen de relevés de neige intensifs couplés à un modèle de fonte à distribution spatiale, de façon à obtenir une information plus exacte sur la quantité et l'étendue de neige avant et durant le printemps. Au printemps de fréquentes embâcles rendent difficile la prise de données hydrométriques précises nécessaires à la détermination de l'écoulement. La variation du niveau de gel dans le sol contrôle la capacité d'emmagasinement de l'eau dans le sol, et cette variation doit être mesurée régulièrement au printemps et à l'été afin d'évaluer les changements d'emmagasinement.

Quand ces problèmes sont résolus, il devient possible de déterminer correctement le bilan hydrique des bassins artiques. Ces déterminations sont d'une grande valeur dans l'inventaire des ressources hydriques du nord canadien.

INTRODUCTION

The Arctic, is the area north of the tree-line, that spans about one-quarter of the land surface of Canada. Very little hydrological information is available for this vast region, particularly for the barren and remote High Arctic which occupies a large part of the Arctic archipelago (Fig.1). There, the physical environment is characterized by extreme and persistent coldness. For over half a year, there is a net loss of radiation energy and even during the periods with long daylight hours, the extensive snowcover reflects much of the incoming solar radiation. The result is the formation and maintenance of permafrost (or earth materials with temperature $\leq 0°C$ for at least two consecutive summers) which continuously underlies the entire area. As yet, we do not have an accurate inventory of its water resources, and this prompted Hare & Hay (1971) and Lvovitch (1973) to exclude the Arctic archipelago from their analyses of regional water balance.

The water balance offers a hydrological framework that allows the assessment of water gained, lost and stored in a drainage basin for a given period:

$$ds/dt = M + R - E - Q \qquad (1)$$

where M is snowmelt, R is rainfall, E is evaporation, Q is runoff and ds/dt is the rate of change of storage. Water balance investigations, though useful, have been attempted only at a few small basins in the High Arctic. The harsh climate and the remote location conspire to make Arctic research difficult. This paper will discuss some of the major problems and methods pertaining to small basin water balance studies in the High arctic, and will summarize the findings of one such study for illustration purposes.

PROBLEMS OF WATER BALANCE STUDIES

Inaccurate and insufficient hydrometeorological data has long prevented annual water-balance from being calculated. Added to this problem was the poor understanding of many of the processes operating in the Arctic environment, limiting the interpretation of field observations and making it difficult to extend in space and in time the result of any one study. Since the 1970's, research has increased on various elements of the Arctic hydrological system (Woo, 1986) including precipitation (Cogley & McCann, 1976; Woo & Marsh, 1978), snowmelt (Heron & Woo, 1978), evaporation (Addison, 1977; Ohmura, 1982), slope runoff (Lewkowicz & French, 1982; Woo & Steer, 1982), and streamflow (McCann & Cogley, 1972; Woo & Sauriol, 1980). These advances did not overcome the difficulties of computing the water balance because the short-term nature of the studies prevented the determination of representative mean values of the water balance components.

The technical problems arising from water balance studies can be solved by carefully documenting the spatial and temporal changes of the various elements in equation (1). Precipitation ($P = M + R$) measurement has long suffered inaccuracies because of poor catch efficiency of gauges under windy conditions (Goodison, 1978) and because of the frequent trace events that cannot be recorded by conventional means (Woo & Steer, 1979). Snowfall is especially prone to large measurement error. Woo et al. (1983) found that the total snowfall recorded at weather stations represented only about 40 to 60 percent of the winter accumulation in nearby drainage basins. One way to handle this problem is to conduct an intensive basin-wide snow survey at the end of winter (Wedel *et al.*, 1977; Woo & Marsh, 1978). Since the snow does not melt throughout the long polar winters, the survey should provide a good measure of total snow accumulation. By dividing the basins into different terrain units each with an area a_i, and intensely sampling the snow to obtain mean depth (d_i) and mean density (ρ_i) for each unit, the surveys should provide satisfactory estimates of the mean snow condition for the basin (PS)

$$PS = \sum_{i=1}^{n} d_i \, \rho_i \, a_i / \sum_{i=1}^{n} a_i \tag{2}$$

where n terrain units make up the basin.

Evaporation is usually determined from a single site and the computed values are assumed to be applicable to the entire basin. This assumption is not valid for the snowmelt period because when the basin snow cover breaks up into patches, only the snow-free zones undergo evaporation and the snow may or may not sublimate (Fig.2). It is therefore necessary to couple snow distribution with evaporation during the melt period. This can be achieved by continuously updating the basin area that becomes snow-free. Continuing with the terrain unit approach, a unit becomes snow-free when $ps_i(t) \le 0$, where

$$ps_i(t) = ps_i(t-1) + p_i(t) - m_i(t) \tag{3}$$

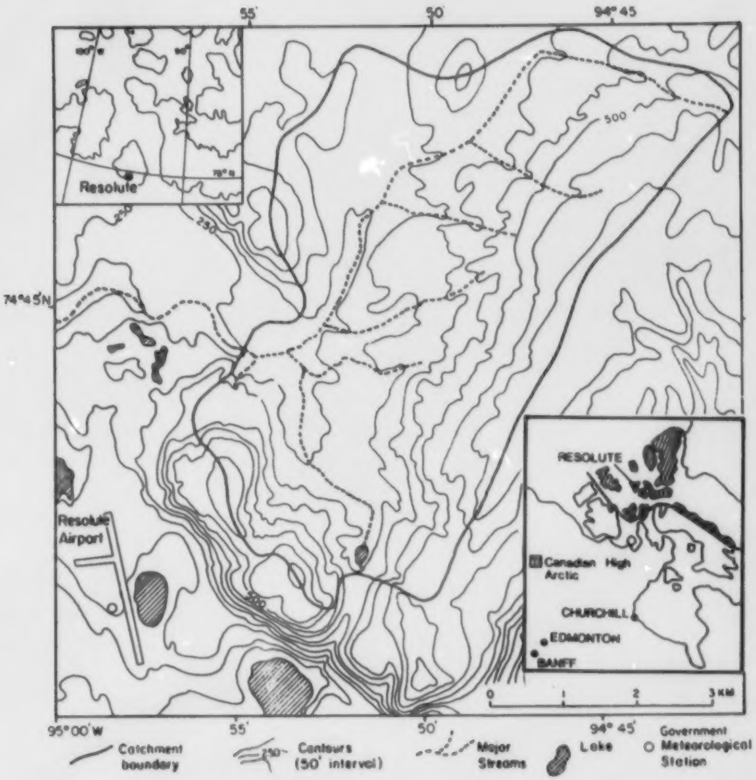
with $ps_i(t)$ being the snow stored at unit i on day t, p_i being new daily snowfall and m_i the daily melt rate at unit i which may be calculated using the energy balance approach (e.g. Heron & Woo, 1978). Then, basin evaporation (E) on day t can be obtained by

$$E(t) = \sum_{i=1}^{k} e_i(t) \quad a_i / \sum_{j=1}^{n} a_j \tag{4}$$

with k terrain units being snow-free on day t. The value of evaporation for unit i (e_i) can be obtained using microclimatic methods (e.g. Priestley & Taylor, 1972). As the ground dries out in spring, evaporation will be affected by the spatial variation of moisture available at the ground surface. Before extending the point estimate to various terrain units basin conditions must be ascertained to see if they are similar to those at the site where evaporation is determined.

Sublimation of snow may be substantial in some parts of the High Arctic. Ryden (1977) estimated that a quarter of the winter snow cover may be lost to sublimation. For many other areas, however, the amount of water loss through this process is much less, though the equivalent energy loss may be considerable because of the large latent heat involved.

Runoff in the lower latitudes can often be measured with ease at the basin outlet by establishing a stage-discharge rating curve and applying the curve to the river stage monitored continuously by a water level recorder. This cannot be done in the Arctic during break up. At that time, the valleys are deeply filled with snow, blocking the advance of meltwater runoff. The river has to incise through the snow and sometimes water is impounded behind large snowdrifts to form temporary reservoirs, the breaching of which generates floods pulses downstream (Fig.3). The morphology of the snow-lined channel alters continuously (Woo & Sauriol, 1980) making it impossible to obtain any stable stage-discharge relationship. Streamflow has to be measured directly during this peakflow period. This is a hazardous operation because of the fast flow through unstable channels lined with snow and ice.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Catchment boundary
Contours (50' interval)
Major Streams
Lake
Government Meteorological Station

FIG.1 Location of Canadian High Arctic and topography of McMaster River basin.

Change in basin storage is difficult to measure directly. Many workers have assumed that the annual change is negligible or have computed storage change as a residual term of water balance. Because annual storage change may actually not approach zero, the storage component if left as residual term inevitably incorporates the errors for the other water balance components. This can be avoided only if all the other terms on the right hand side of equation (1) are evaluated accurately.

Besides technical problems, logistical difficulties are encountered because of the isolated field locations. Air transportation is often required to carry the personnel and the freight to the sites, and this can be prohibitively costly. Fortunately, most hydrological activities are concentrated within a short thawed season that reduces the field time. Additionally, the Polar Continental Shelf Project of the Department of Energy, Mines and Resources offers invaluable support to worthy field projects in the Arctic (Hobson & Voyce, 1974-87). Four weather stations that service the High arctic islands provide year-round data which may be useful when properly calibrated for the field sites. Finally, working in the harsh and isolated situation requires a certain level of mental aptitude and physical fitness, the lack of which can disrupt a well-planned research project.

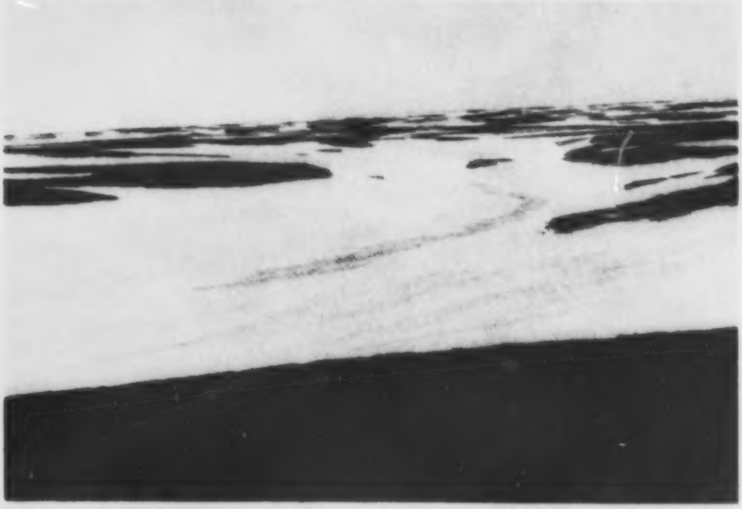

FIG.2 Mossaic of show-covered and snow-free areas in McMaster basin during the 1977 snowmelt period. The snow-free zones experience evaporation while the snow covered sites are melting. Initial runoff in the stream begins as snow slush (grey area near centre of photograph).

EXAMPLE OF WATER BALANCE STUDY

A six-year water balance study was carried out at McMaster basin near Resolute, Cornwallis Island (74° 45'N, 94° 50'W). This basin (area 33 km^2) has an elevation range of 85 to 200 m a.s.l. and is located near a weather station (Fig.1). Gravel and loam form the dominant surface material and patches of tundra vegetation are scattered over an otherwise barren landscape. The weather station reports a January mean minimum of -36°C and a mean July maximum of 7°C. Continuous permafrost is maintained at 0.2 to 0.7 below the ground surface. The snow cover lasts for about nine months in each year, with such activities as evaporation and runoff being confined between late June and mid-September.

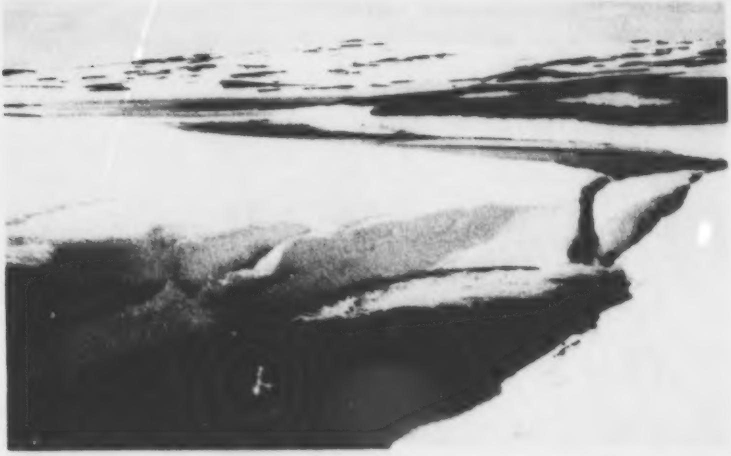

FIG.3 A snow dam along McMaster river is being breached by the spring runoff, resulting in rapid drainage of the snow-impounded reservoir.

Detailed description of field and computation methods are given in Woo *et al.* (1983) and need only be summarized here. The snow cover is always uneven because drifting removes the snow from the exposed sites to the more sheltered topographical depressions. Snow surveys were carried out across different terrains at the end of each winter to determine total basin snow storage. Snowmelt at each terrain unit was calculated daily in spring, using an energy-balance approach (Heron & Woo, 1978), and summed to yield total melt for the basin. Because the snow distribution was uneven at the end of winter, the snow cover quickly broke into patches as melting began. When a certain terrain unit became free of snow, the magnitude of its evaporation depend on

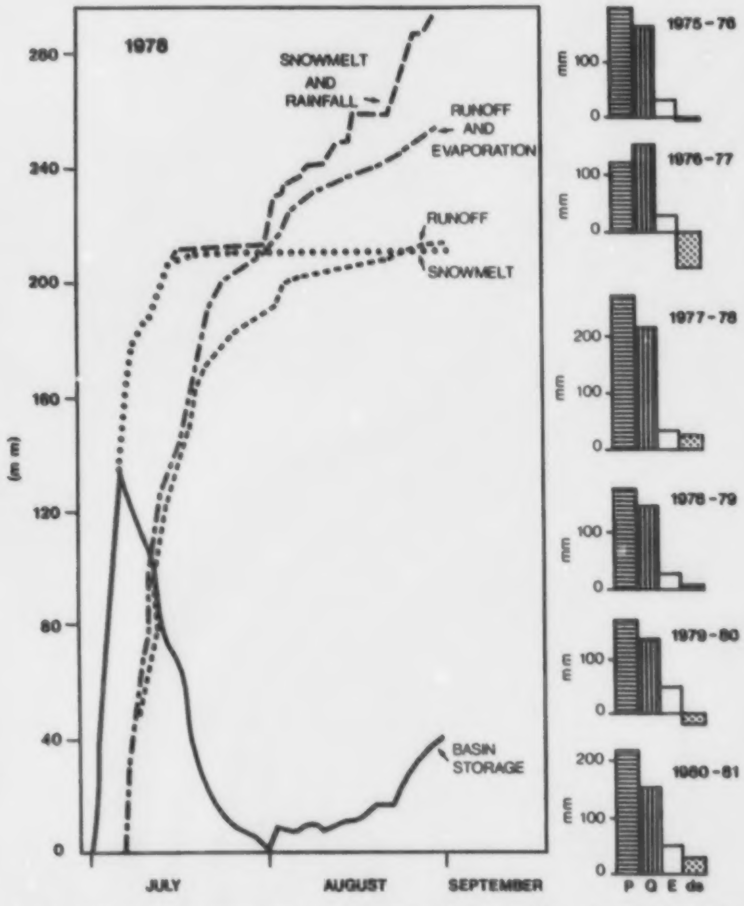

FIG.4 Daily water balance for McMaster River Basin in 1981, and annual water balance for 1975-81. (P = Ppt, Q = runoff, E = ET, ds = change in storage)

the available amount of energy and surface soil moisture (Marsh *et al.*, 1981). Rainfall was measured by a network of gauges and streamflow was obtained at the outlet of the basin, and a "water year" was considered to span the timebetween the first significant snowfall in September of the first year when the snow would stay for the winter, and the arrival of snowfall a year later.

The cumulative daily snowmelt, rainfall, evaporation, runoff and change in storage (computed as a residual) were recorded for the 1978 field season (Fig.4). Snowmelt began late that year (July 1) but three-quarters of total winter snow accumulation was depleted within one week. Evaporation was negligible until runoff began on July 6. With the release of a large amount of meltwater, but a comparatively low amount of water loss, a large volume of water was stored in the basin. Field observation showed that the bulk of this storage was retained first in deep valley snowpacks which became saturated by meltwater draining from the slopes. As the ground began to thaw, an increasing amount of water was stored in the soil. Peak runoff occurred once an integrated channel flow network was established in the snow-filled valleys (Woo & Sauriol, 1980) to drain most of the basin's stored water. Evaporation, though low in magnitude, increased gradually. Storage was much reduced by late July and dry conditions became prevalent. Rainfall in August occasionally raised the streamflow but a sizeable portion of the precipitation went into replenishing the basin's storage. Streamflow and evaporation declined by September, as freeze-up began. An excess of storage at the end of summer extended into the subsequent spring, showing that the net change in storage at the end of the year is not negligible.

TABLE 1 Summary of water balance for five drainage basins in the Canadian Arctic archipelago.

Basin	Location	Area (km^2)	Surface cover	Period of study	PPT (mm)	ET (mm)	RO (mm)
F2 watershed Skalugad Fiord (Church, 1974)	69°N 69°W	2.5	Mainly vegetated bedrock and thin drift	1976	616	154	462
Intensive watershed (Ryden, 1977)	76°N	0.12	63% vegetated and bare soil, 12% water, 25% bedrock	1972-74	185	101	84
Gully River Truelove Inlet Devon Island (Holecek & Vosahlo, 1975)	76°N 85°W	22.4	Barren polar desert	1972-73	198	?	250
Snowbird Creek Western Bathurst Island (Wedel et al., 1977)	76°N 101°W	80	Mainly barren polar desert and bedrock. 10% vegetated mainly in lowland	1976	158	?	156
McMaster basin (Woo et al., 1983)	75°N 95°W	33	Mainly barren polar desert and bedrock	1976-81	190	38	158

Various components of the annual water balance for 1975-1982, including precipitation, runoff, evaporation and net storage change have been calculated (Fig.4). In all years, runoff accounted for a large part of annual precipitation. Year-to-year fluctuations in precipitation and runoff were noticeable but variation in the magnitude of evaporation was the most conservative. The computed annual change in storage also varied and showed an excess in some years, and a deficit in others. Over six years, annual precipitation averaged 190 mm, runoff 158 mm, and evaporation 38 mm. The computed net storage deficit for the entire study period was 34 mm.

DISCUSSION

Results from McMaster basin can be compared to several other High Arctic water balance studies that spanned one to three years, using direct measurement of at least two of the water balance components (Table 1). All but one of the these basins had low precipitation of about 200 mm, confirming that many part of the High Arctic are polar deserts (Bovis & Barry, 1974). The high value for the Ekalugad Fiord (Church, 1974) is due to the heavy orographic precipitation of eastern Arctic. Runoff for all but the "Intensive Watershed" (Ryden, 1977) accounted for most of the total precipitation because the proximity of the impervious permafrost near the surface helps to shed most to the meltwater or the heavy rainfall. The abundance of wetland and ponds at the "Intensive Watershed" detains much of the surface flow and enhances evaporation at the expense of runoff. The long-term change in storage was assumed or computed to be small, except for "Gully River" which showed a large deficit for 1978. Holocek & Vosachlo (1975) argued that water was released from ground ice storage to balance this deficit, but Ryden (1977) suggested that this was an artifact of underestimation of the snow precipitation because of the unknown quantity of snow held in the deep ravines.

These studies represent disparate efforts to conduct water balance research on a small basin scale in the High Arctic. The accuracy of most results is not known because the error terms were not reported. This paper has outlined the need to collect spatially distributed hydrological data, extended over a period of several years, to obtain representative values for basin water balance. While basin water balance are feasible, regional inventory of water resources remains a formidable task. Further development of the Arctic will demand more hydrometeorological information and this will spur the extension of small basin studies to a regional scale.

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Lake hydrology studies in the Mackenzie Delta, N.W.T.[1]

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ABSTRACT A study of lake basins in the Mackenzie Delta, N.W.T. was initiated in the early 1980's with the aim of providing an understanding of the hydrological processes controlling lake levels. This research originated in response to proposals of hydroelectric development in the Mackenzie Basin and the subsequent concern over the effect on lake levels and the resultant ecological consequences in the Delta. A research basin was used because it was felt that this would provide the necessary comprehensive information on the processes controlling lake levels. The principal disadvantage was that a single research basin could not deal with the spatial variation in lake regime, both within small areas in the delta, and over the entire 200 by 60 km extent of the delta. Since it was impossible to fully instrument enough basins to provide a representative sample of lake types, three other studies were designed to provide information on the spatial variability of lake regimes. First, less detailed basin studies were carried out at three sites within the delta to determine changes in lake regime over the north-south extent of the delta. Second, aerial photographs were taken across the southern, middle, and northern delta during the spring period to document ice break-up, an important process controlling water levels in the main channels. Third, measurements of lake elevation, in conjunction with analysis of 25 years of water level data provided information on the spatial variation in lake flooding within a single area of the central delta. Only by carrying out this series of integrated studies were we able to meet the overall objectives of this study.

RÉSUMÉ Au début des années '80, on a mis sur pied une étude de bassins avec lacs dans le delta du Mackenzie, T.N.O., afin de mieux comprendre les processus hydrologiques qui contrôlent le niveau des lacs. Cette recherche faisait suite aux inquiétudes concernant l'influence de projets de développement hydroélectrique proposés pour le bassin du Mackenzie sur le niveau des lacs et les conséquences écologiques de cette influence sur le delta. L'approche par bassin fut retenue car il semblait que cette approche fournirait de l'information détaillée sur les processus contrôlant le niveau des lacs. La lacune principale était qu'un seul bassin de recherche ne pouvait tenir compte des variations spatiales des régimes lacustres, variations à l'intérieur de régions du delta, et à la grandeur du delta de 200 par 60 km de superficie. Comme il était impossible d'instrumenter assez de bassins pour obtenir un échantillonnage représentatif, trois autres études ont été mises sur pied afin de cerner la variation spatiale dans le régime hydrique des lacs. Premièrement, trois autres bassins du delta ont été étudiés de façon moins exhaustive afin de déterminer les changements des régimes lacustres du nord au sud du delta. Deuxièmement, des photographies aériennes de la debâcle printannière, un important facteur dans le contrôl du

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[1] NHRI contribution No. 88032.

niveau des lacs dans le chenal principal, ont été obtenues pour des sections localisées dans les parties nord, sud et centre du delta. Troisièmement, des mesures d'élévation des lacs, conjointement à l'analyse de 25 ans de données sur le niveau des eaux, a fourni de l'information sur l'inondation des lacs dans une région du centre du delta. Ce n'est que par la réalisation de ces études intégrées que nous avons pu atteindre les objectifs de base de l'étude.

INTRODUCTION

In the late 1970's B.C. Hydro proposed the development of two hydro-electric dams on the Liard River (B.C. Hydro, 1981). It was soon realized that the resulting changes in the hydrologic regime of the Liard River could be wide ranging and might even affect the Mackenzie Delta, over 1700 km downstream. Although the nature of the resulting changes, in both the physical and biological systems, were not well understood, there was considerable concern over the possible effect of the proposed Liard development on the Mackenzie Delta ecosystem. The validity of such concerns was illustrated by the Peace-Athabasca Delta experience in the 1960's and 1970's where decreased water levels resulted in significant environmental problems (Peace-Athabasca Delta Project Group, 1973). As was the case in the Peace-Athabasca, the primary uncertainty regarding potential impacts for the Mackenzie Delta focused on the effect of flow regulation on water levels in the vast number of delta lakes. These lakes, which cover approximately 25% of the Mackenzie Delta, support large and diverse populations of plants, fish, and wildlife, and are an important staging and nesting area for waterfowl. If a significant decrease in lake levels occurred, it was postulated that there would be a severe decline in the wildlife populations with resulting implications to the economy of the five communities in the Mackenzie Delta region.

In light of these environmental concerns, a study of lake hydrology in the Mackenzie Delta, N.W.T. was initiated in 1980 by the National Hydrology Research Institute. The principal objective was to improve the understanding of the hydrological processes controlling lake levels to allow water resource managers to make responsible and informed decisions with regard to development in the Mackenzie River Basin.

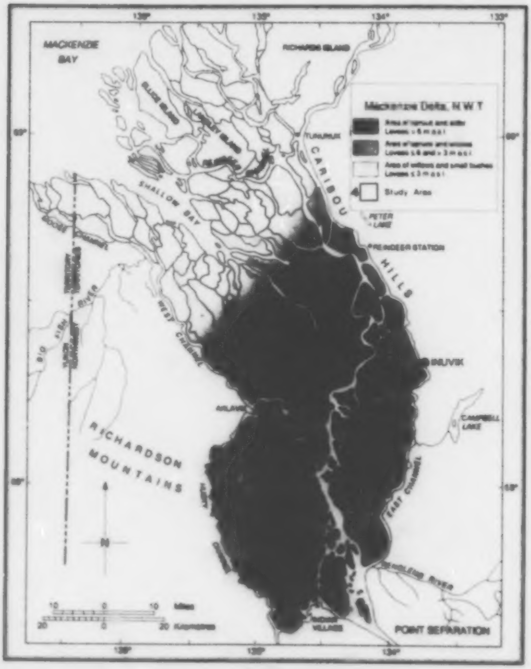
Specific objectives of the initial lake hydrology project were to:

(1) determine the relative importance of the various processes controlling lake levels;
(2) describe the spatial and temporal variations in hydrologic regime of the delta lakes, and
(3) develop a predictive model of lake levels.

Further work has since aimed at determining the influence of the hydrologic regime on the sediment and nutrient balance of delta lakes, which has important implications for the biological productivity of the lakes.

RESEARCH PLAN

In devising an experimental plan, the decision was made to establish a research basin in the Mackenzie Delta where detailed work could be carried out within a small, "representative" basin. It was felt that this approach would provide the necessary information on the hydrologic processes controlling lake levels. In the early 1980's, the "NRC Lake" basin (Fig.1 and 2) was chosen as a research site because it had a well-defined basin and the elevation with which it is perched above the main channel system was equal to the mean for lakes in this part of the delta. In addition, Johnston & Brown (1964) carried out detailed permafrost studies at this site. Because of the proximity of NRC Lake to Inuvik, the long-term climate and water level records available from the Atmospheric Environment Service and Water Survey of Canada were considered to be representative of conditions at the study basin. At the NRC Lake site, studies of water level, snow-melt run-off, flooding by the Mackenzie River, flow in reversing lake channels, evaporation, ground water flow, lake water balance, and sedimentation are ongoing. The instrumentation and analysis techniques used in these studies have been described in Marsh (1986, 1988), Marsh & Bigras (1988), and Marsh & Ferguson (1988).


MACKENZIE BAY
RICHARDS ISLAND
Mackenzie Delta, N.W.T.
Study Area
CARIBOU HILLS
SHALLOW BAY
PETER LAKE
REINDEER STATION
WEST CHANNEL
INUVIK
AKLAVIK
CAMPBELL LAKE
RICHARDSON MOUNTAINS
EAST CHANNEL
POINT SEPARATION
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10 0 10 Miles
20 0 20 Kilometres

FIG.1. Location of study sites in the Mackenzie Delta. NRC Lake research basin is located in area 4, near Inuvik.

It was realized, however, that because of the unique aspects of the delta, a single research basin would not allow us to meet all of our original objectives. The primary problem was the tremendous spatial variation in lake regimes. Within small areas of the delta, lake regime varies with lake elevation relative to the main channels. Over the north/south extent of the delta, it varies due to changes in levee height, discharge regime of the main channels, ice jamming, and the influence of storm surges in the Beaufort Sea.

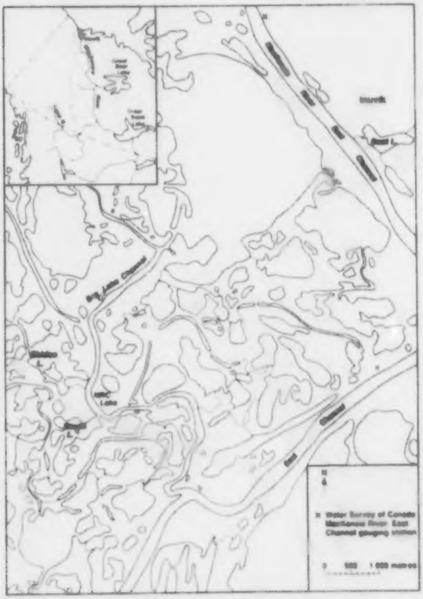
Inuvik
Big Lake Channel
NRC Lake
N
Water Survey of Canada Mackenzie River East Channel gauging station
0 500 1 000 metres

FIG.2 Location of NRC Lake in study area 4 near Inuvik, N.W.T. Note the large number of lakes, small lake sizes, and the large network of chanels which link many of the lakes. Also shown are the ofher study lakes within area 4.

The solution to the problem of spatial variation, was the establishment of three other studies designed to complement and enhance those at the NRC Lake research basin, thus forming an overall framework of delta hydrologic studies. First, less detailed small basin studies were initiated at three research areas located approximately 100 km apart (Fig.1). Within each area, two lakes were chosen. One low-elevation or connected lake, and the other a higher-elevation or perched lake. At each of these sites, basic data such as water level, snow cover, ice thickness, water and air temperature, and precipitation were collected. The methodology utilized in these studies has been described in Bigras (1986, 1987). Second, in conjunction with visual observations of ice conditions, aerial photographs were taken across the southern, middle, and northern delta during spring break-up. This provided a description of the spatial and temporal variations in ice jamming, an important process controlling water levels during the spring ice break-up. These studies have been described by Bigras (1988). Third, measurements of the elevation of over 130 lakes in Area 4, were combined with the analysis of 25 years of Mackenzie River East Channel water level data, to provide information on the flooding regime of the complete elevation range of lakes in this area of the delta. The techniques used have been described by Marsh & Hey (1988).

RESULTS

These series of studies have allowed us to make significant advances in our understanding of the hydrologic regime of delta lakes, and to meet most of our original goals. In order to demonstrate the advantages of the integrated approach, the following section will briefly outline the results from a single aspect of this study, the dominance of spring flooding and spatial variations in its magnitude.

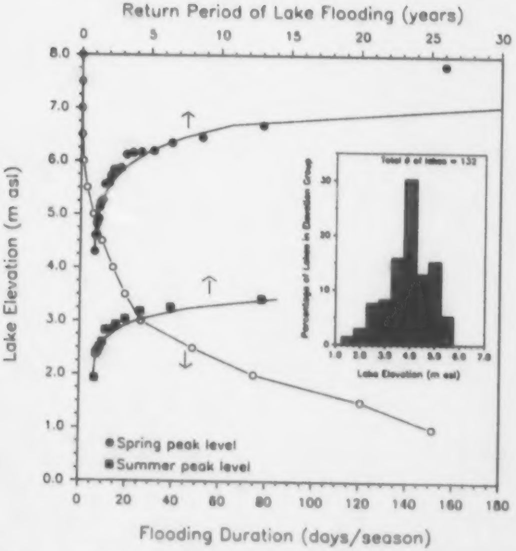

FIG.3 Summary of duration and frequency of lake flooding as determined from 25 years of record for East Channel at Inuvik and the elevation of lakes in area 4.

The studies at the NRC Lake research basin and at the less detailed basins have clearly demonstrated that spring break-up dominates the hydrologic regime of the delta, with the spring peak water levels in the main channels always greater than the summer peak water levels (Fig.3 and 4). During this period of high water levels, water enters the delta lakes through small channels connecting the lakes to the main Mackenzie River channels. This discharge dominates the lakes water balance. Detailed water balance studies at NRC Lake have shown that without this influx of water from the Mackenzie River, NRC Lake would experience a negative water balance, and declining lake levels. This would occur for two reasons. First, lake evaporation is larger than the open water period precipitation, and almost as large as the mean annual precipitation recorded at the Inuvik A.E.S. weather station. Second, snow-melt run-off is negligible because of the high infiltration capacity of the frozen soils. The only documented example of declining lake levels over a number of years is for a lake in Area 2. It was last flooded by the Mackenzie River in 1982, and the lake level declined about 2.5 m between the spring of 1982 and the fall of 1985.

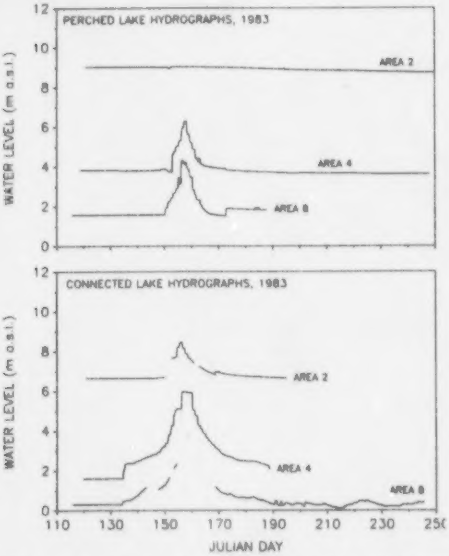

FIG.4 Lake levels for connected and perched lakes in areas 2, 4, and 8 in 1983.

Within a given study area, the main factor controlling channel discharge into the lakes is the lake elevation, with inflow decreasing with increasing lake elevation. This variation in discharge regime is illustrated in Figure 3, which provides data on the frequency and duration of lake flooding versus lake elevation and the percentage of lakes in each elevation band. In this example, lake flooding is defined as occurring when the main channel water level is above the lake elevation, and discharge is into the lake through the lake connecting channel. Using Area 4 as an example, Fig.3 shows that the return period of lake flooding in the spring varies from annually for the 67% of all lakes below 4 m asl, to every 4 years for the highest elevation lakes. Fig.3 also shows that the duration of flooding decreases rapidly with increasing lake elevation.

Similar variations in regime also occur over the north-south extent of the delta. They are due primarily to changes in levee heights from 10 m a.s.l. in the southern delta near Area 2 to less than 3 m a.s.l. in the northern delta (Area 8). As a result there are substantial variations in the main channel regime, lake elevations, and therefore in lake regime. For example, lakes in the southern delta are at a higher elevation, and are the last to experience the effects of back-water flooding in the spring, and have the smallest increase in water level (Fig.4). The highest elevation lakes in this area are flooded infrequently and experience declining water levels over the summer period (Fig.4). As you move further north to the central delta, the lakes are lower in elevation, are flooded earlier and consistently experience the greatest water-level fluctuations (Fig.4). Lakes in the northern delta (Area 8) have much lower elevations and are among the first to be flooded in the spring (Fig.4). The increase in water levels from late winter values to peak flood levels is greater in the northern than the southern delta, but not as great as the central delta.

The primary conclusion from these results is that delta lakes rely on spring flooding by the Mackenzie River. If the spring water levels in the main Mackenzie Delta channels are reduced due to hydro-electric development, lakes would flood less frequently and would experience declining water levels or might even disappear completely. This would have serious consequences for wildlife in the delta. The higher elevation lakes which currently do not flood annually in the spring are the most sensitive to changes in the Mackenzie River spring water level regime. These include about 30% of lakes in Area 4 and the majority of lakes in Area 2. There are few, if any lakes of this type in Area 8.

DISCUSSION

Our work in the Mackenzie Delta has illustrated both the advantages and disadvantages of the research basin approach in an environment such as the Mackenzie Delta. It has proven very successful in documenting the magnitude and relative importance of processes such as snow melt run-off, lake evap[illegible]ation, ground-water flow, and channel discharge for a single lake. This c[illegible] not have been achieved using any other approach. However, due to financial and logistical restrictions which limited the number of research basins that could be instrumented, it was not possible to deal with the spatial variation in lake regime using the research basin approach alone. This problem was partially solved by using an integrated series of studies, of which one component was a research basin. However, our analysis of the spatial variations in lake flooding was limited by two factors. First, the lack of appropriate satellite remote sensing techniques for recording the progression of lake flooding during the spring breakup period. Unfortunately, a satellite is not yet available which can meet our requirements for all weather operation, repeat imaging every few days, and a spatial resolution of 20 to 50 m. The second limitation is the lack of long-term water-level data for the main channels in the Mackenzie Delta. Only East Channel at Inuvik has sufficient data for a statistical analysis. It may be possible to overcome this problem using lake sediment cores to provide proxy data. This work was initiated last year.

These delta hydrologic studies are continuing, with initial results described in a number of reports and papers referred to earlier in this paper. Because of the importance of the hydrologic system to the Mackenzie Delta ecosystem, these hydrologic studies have been used by other delta researchers for environmental assessment (B.C. Hydro, 1985; Mackenzie River Basin Committee, 1981), and limnological studies (Fee *et al.*, 1988). From a management point-of-view, the postponement of the B.C. Hydro Liard River project has delayed the requirement for decisions concerning hydro-electric development in the Mackenzie Basin. However, since other environmental issues, such as hydrocarbon development and rising sea level, have become prominent in the last few years, the need to properly manage the water resources of the Mackenzie Delta is still a prime concern. The work provided by the studies described in this paper will enhance our capabilities to provide the required scientific advice on environmental problems related to the water resources of the Mackenzie Delta.

ACKNOWLEDGMENTS

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SECTION II

BASIN RELATED RESEARCH

CANADIAN HYDROLOGY SYMPOSIUM (CHS:88)
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Continuous simulation of changes in streamflow due to urbanisation

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ABSTRACT Continuing urbanisation is adversely affecting water resources in urbanising river basins by disturbing flow regimes and downgrading water quality. Such effects have been observed and studied in the Waterford River Basin near St. John's, Newfoundland. The effects of future urbanization on flows in the Waterford River have been studied using both single-event and continuous simulation models. In continuous simulation, reported here, the model developed by the U.S. Environmental Protection Agency has been used and calibrated, with good-to-very-good results, against the available precipitation/streamflow records. The calibrated HSPF model was used to simulate streamflows for several hypothetical land development scenarios. Such simulations indicated that the projected future development will not increase significantly the seasonal or annual streamflow volumes, because of the high conversion of precipitation into streamflow under the existing basin conditions. However, some increased in peak flows and incidence of flooding have been indicated by the simulations. If the basin impervious areas are doubled, the highest peak flows in the basin would increase by about 25%. It is recommended to use the calibrated HSPF model, expanded for water quality simulation modules, in the future management of water resources in the water.

RÉSUMÉ Dans les bassins fluviaux qui connaissent une urbanisation continue, on constate des effets néfastes sur les ressources en eau, soit la perturbation des régimes d'écoulement et la diminution de la qualité de l'eau. Nous avons observé et étudié de tels effets dans le bassin de la rivière Waterford près de St. John's, à Terre-Neuve. Pour étudier les effets de l'urbanisation sur l'écoulement de la rivière Waterford, nous nous sommes servis d'un modèle de phénomène unique et d'un modèle de simulation continue. En ce qui concerne la simulation continue, qui nous intéresse ici, nous avons utilisé le modèle HSPF de l'Environmental Protection Agency des É.-U., que nous avons étalonné avec des résultats bons à très bons grâce aux relevés disponibles sur les précipitations et sur l'écoulement. Le modèle étalonné a servi à simuler l'écoulement pour plusieurs scénarios, hypothétiques, d'aménagement des terres. Selon les simulations, les projets d'aménagement n'entraînent pas d'augmentation marquée des volumes saissonniers et annuel de l'écoulement, et ce, en raison du rapport de conversion élevé des précipitations à l'écoulement pour les conditions actuelles du bassin. Nous avons remarqué toutefois une certaine agumentation de l'écoulement maximal et des épisodes de crue. Pour un doublement de la surface imperméable du bassin, on obtient une augmentation de l'écoulement maximal absolu de 25%. Nous recommandons que soit utilisé le modèle HSPF étalonné, et doté de modules de simulation de la qualité de l'eau, dans la gestion future des ressources en eau, dans ledit bassin.

INTRODUCTION

In response to the concerns about the adverse effects of urbanisation on water resources in the Waterford River Basin (Newfoundland Environment, 1978), a five-year federal-provincial study, referred to as the Waterford River Basin Urban Hydrology Study, was conducted from 1980 to 1985. The main study objectives were to examine the processes causing changes in the hydrologic regime of the Waterford River, to establish a modelling capability for simulating such changes, to develop solutions to specific water management problems in the studied basin, and to develop guidelines for implementation of similar solutions elsewhere in Newfoundland. The study has been successfully completed and its results are discussed elsewhere (Ullah *et al.*, 1988). The paper that follows deals with one of the study components, continuous simulation of streamflow in the Waterford River Basin and the use of such simulations for investigating the impact of future urban development in the basin.

STUDY AREA

An upper part of the Waterford River Basin, located near St. John's, Newfoundland, measuring 53 km^2, was selected as the study area. The main stream in the basin is the Waterford River, which flows northeasterly over a distance of about 14 km and discharges into St. John's Harbour. Its main tributary, South Brook, flows through the undeveloped part of the basin and discharges into the Waterford River just upstream of the hydrometric station at Kilbride.

The land use in the basin was reported by Jones (1986) as follows: forest - 33%, unproductive land - 29%, urban areas - 19%, agricultural areas - 11%, and transitional land use - 8%. The approximate population of the study area is about 30,000 persons. The impervious area in the basin was estimated at 2.65 km^2. The basin geology and soil characteristics indicate that precipitation and snowmelt are largely converted into runoff with little loss by infiltration into the ground (Batterson, 1984; King, 1984).

The climate in the study area is moderated by the sea. The average annual precipitation of 1514 mm y^{-1} is distributed, on the average, over 207 days in a year. The annual evapotranspiration in the basin is rather low, less than 300 mm (Ng & Marsalek, 1987). High streamflows occur in the spring, as a result of the combined effect of rainfall and snowmelt, or in late fall. Low flows occur in summer or winter months. The extreme flows observed in the Waterford River at Kilbride, from 1974-84, were 0.13 $m^3\ s^{-1}$ and 66.1 $m^3\ s^{-1}$, respectively.

STUDY APPROACH

One of the important trends noted in recent urban developments is the acceleration of the urbanization process induced by technological changes coupled with socio-economic demands. Fast expansion of urban developments in the study area was of concern and, consequently, it was desirable to evaluate the impact of anticipated future land use changes on the hydrological regime of the Waterford River. Recognizing the short duration of the study, it was unlikely that changes in the river regime could be observed during the study period. Consequently, the general strategy was to establish calibrated models of the river response and to use such models to predict regime changes arising from future land use changes. For this purpose, two models were used, an event model, HYMO, and a continuous simulation model, Hydrologic Simulation Program - Fortran (HSPF) (U.S. Environmental Protection Agency, 1980). When selecting these models, it was recognized that for analysis of flow peaks the event model might be sufficient. However, the continuous simulation HSPF model offers additional advantages, because it can simulate both high and low flows, and can be easily expanded to water quality simulations in the future and serve for integrated water management in the basin.

A three-year data base, established during the Waterford River Basin Study (Ullah *et al.*, 1988), was sufficient to support only the quantity modules of HSPF and could be used to calibrate the model. The calibrated model was then applied to three hypothetical future land use scenarios assuming various increases in the basin imperviousness (Ng & Marsalek, 1987). Such scenarios cover a wide range of conditions which could possibly materialise during the periods of economic expansion. The results of such investigations follow.

RESULTS AND DISCUSSION

Special physiographic and climatic features of the basin lead to a very high conversion of precipitation into streamflow, in the order of 80-90%. Although such values are unusual compared to the typical examples given in hydrologic handbooks, they are common in many river basins of Newfoundland (See Ullah et al. this proceedings). For the Waterford River Basin data, the average conversion of precipitation into streamflow was 82% (Ng & Marsalek, 1987). Using these data, the HSPF model was calibrated for the annual balance, seasonal balances, and individual event peak flows. The results of such calibrations were rated as good-to-very-good, using the existing calibration criteria. The annual observed and simulated balances were matched within a few percent, the calibrated monthly values were within ±15%, and the hydrograph peak flows, for flows larger than 6 $m^3 s^{-1}$, were within ±5% of the observed values (Ng & Marsalek, 1987).

Following this calibration, the HSPF model was applied to three hypothetical land use scenarios assuming increases in the catchment imperviousness by 50, 100 and 200%. It was noted that the streamflow volume increased just by one percent even for the greatest increase in the basin imperviousness.

Urbanization generally increases surface runoff and streamflow discharges as a result of two processes - increased volume and speed of runoff. Increased runoff volumes are caused by reduced rainfall abstractions resulting from an increased imperviousness of the urbanized basin. Increased speed of runoff is caused by reduced times of concentration resulting from faster hydraulic transport in the urbanized parts of the basin. The simulated data indicate that there are practically no changes in the simulated streamflow volumes as a result of increased imperviousness. This follows from the very high conversion of precipitation into streamflow in the basin, which is given by basin geology and climate. Consequently, any future increases in river discharges can be caused only by increased speed of runoff (reduced times of concentration).

When examining the changes in peak flows shown in Fig.1, some increases in peaks are observed for imperviousness increases equal to or greater than 100%. Thus, increased speed of runoff leads to some increases in the postdevelopment flows. It appears that for prediction of the effects of urbanisation on flow regimes, the existing models are well suited to detect any changes in streamflow volumes, which may be translated into higher flows. The changes caused by faster runoff are more difficult to evaluate, because they depend on detailed characteristics of postdevelopment land use, including the extent of impervious areas, the percentages of such areas directly connected to sewers, drainage density, etc. Such characteristics cannot be easily predicted, because of changing land use patterns and improved management of stormwater in new developments.

SUMMARY

The HSPF model was successfully used to predict the changes in streamflow caused by progressing urbanization. The results obtained somewhat depart from the conventional views and show a limited sensitivity of the Waterford River Basin streamflow to future development, which is caused by the unique geological and climatological features of the basin. Such features result in high conversion of precipitation into streamflow under the existing conditions with limited urbanization. Progressing urbanization will not increase significantly the volumes of streamflow but will cause some moderate increases in peak flows because of more efficient hydraulic transport in newly developed areas. The detection of such trends would not justify, on its own, the use of the HSPF model which as high requirements in terms of data and computer support. The main benefits of using this model comprise its capability to simulate both high and low flows, and the possibility of a future expansion to include simulations of water quality.

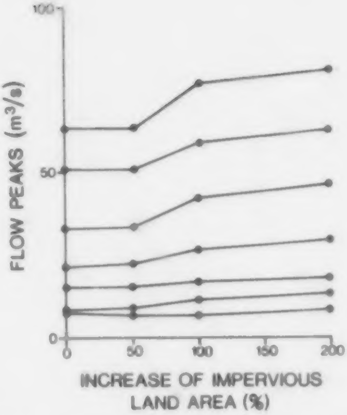

FIG.1 Waterford River Peak discharges simulated for hypothetical future land use scenarios.

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Urbanization effects on streamflow characteristics in Waterford River basin

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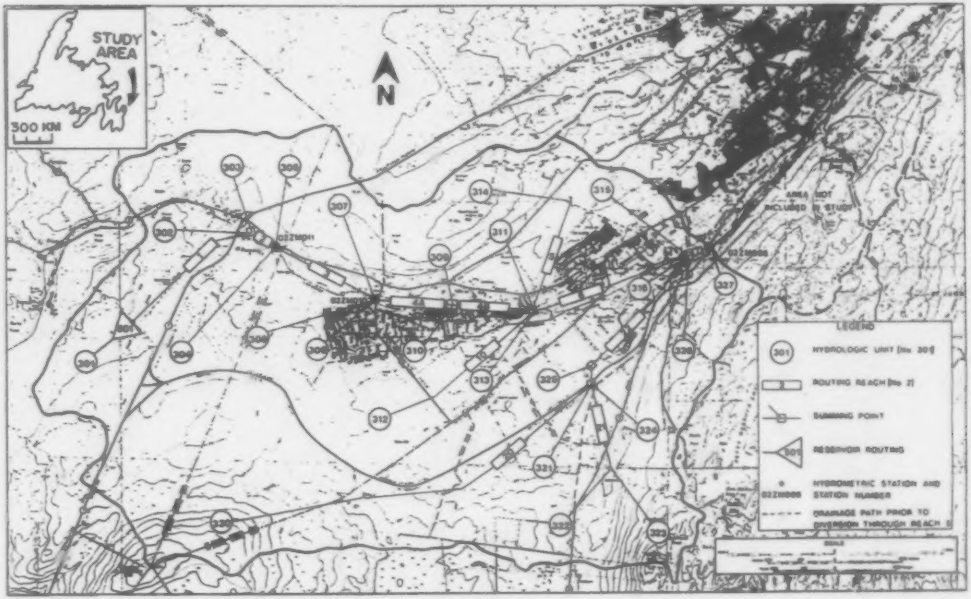
ABSTRACT The process of urbanization brings about significant changes in the land use of a basin e.g., transformation of natural areas into residential, industrial and commercial areas; thereby resulting in a rapid increase in impervious areas. Such changes modify in a variety of ways, the hydrologic behaviour of a basin and invariably results in one or more water management problems such as increased incidence of flooding, continuous deterioration of both surface water and ground water quality, steady decline of ground water levels and rapid disruption of biotic river environment. In this paper, the effects of urbanization on runoff characteristics in Waterford River Basin are examined with the use of a commonly applied hydrologic model (HYMO). The modelling results indicate that runoff characteristics, in general, have been altered. However, significant changes in runoff characteristics are not readily discernable from the results obtained, based on available data for the period of 1974-81.

RÉSUMÉ Le processus d'urbanisation entraîne des changements importants dans l'utilisation des terres d'un bassin, comme par exemple la transformation d'aires naturelles en zones résidentielles, industrielles ou commerciales, avec un accroissement concomitant des zones imperméables. De tels changements modifient de plusieurs façons le comportement d'un bassin, et résultent invariablement en un ou plusieurs problèmes de gestion des eaux tels que l'augmentation dans la fréquence des inondations, la détérioration de la qualité des eaux souterraines et de surface, la chute de la nappe phréatique, et la perturbation de l'environnement aquatique. Dans ce texte, les effets de l'urbanisation sur les caractéristiques d'écoulement sur le bassin de Waterford River sont examinés au moyen d'un modèle hydrologique d'application courante (HYMO). Les résultats des simulations, basées sur les données des années 1974-1981, montrent une certaine altération des caractéristiques générales d'écoulement, mais ces changements ne sont pas significatifs.

INTRODUCTION

Since 1976, a wide variety of water management problems have been experienced in the Waterford River Basin due to urbanization. Similar problems have also been experienced in other urban areas of Newfoundland. In an effort to develop appropriate procedures, guidelines, measures, and management strategies to deal with specific water management problems in urban areas of Newfoundland, the Provincial Department of Environment in cooperation with the Environment Canada commenced a hydrology study of the Waterford River Basin (Anonymous 1978). A number of sub studies were initiated to achieve the overall objectives of the study. One such sub study comprised of investigations into the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02ZM011
02ZM010
02ZM008
AREA NOT INCLUDED IN STUDY
LEGEND
301 HYDROLOGIC UNIT (No. 301)
ROUTING REACH (No. 2)
SUMMING POINT
301 RESERVOIR ROUTING
02ZM008 HYDROMETRIC STATION AND STATION NUMBER
DRAINAGE PATH PRIOR TO DIVERSION THROUGH REACH 8
SCALE

FIG.1 HYMO model schematic for the Waterford River basin.

effects of urbanization on the storm drainage aspect of the Waterford River Basin. The investigations entailed evaluation of the past and present changes in streamflow behaviour in the basin and also examined the potential changes in streamflow behaviour, especially in terms of peak flows.

A review of available models in literature and the assessment of available data set for the study area indicated preference for the use of lumped models (Panu, 1982). Besides, it is difficult to use a model requiring detailed representation of a basin in which urbanization is still in progression. Based on such considerations, it was decided to use the HYMO model to simulate the effects of urbanization on flow characteristics in the Waterford River Basin.

This paper presents the results of various applications of the HYMO model to examine the effects of urbanization on streamflow characteristics in the Waterford River Basin.

DESCRIPTION OF THE STUDY AREA

The Waterford River Basin covers an area of approximately 76.7 km^2 and drains into St. John's Harbour (Fig.1). The upper portion of the basin comprising an area of 53.8 km^2 and lying upstream of the streamflow gauging site at Kilbride constitute the study area. The main stem of the river is 13.5 km long to the Kilbride station. The South Brook, the major tributary, is 11 km long to its confluence, just below Bowering Park. The channel of the main river and tributaries are generally gravel-lined with some areas cobble-paved, where bedrock forms the channel-bed. Soils are coarse textured containing stones, gravel, and boulders (King, 1984). Water movement is largely governed by the overburden material comprising of a very compact, poorly sorted lodgement till with high silt-clay content overlain by a till deposit that is loose, coarse, and more permeable.

There are three recording streamflow gauges (Donovans, Mount Pearl and Kilbride) in the study area (Fig.1). Streamflow data is available since 1973 at the Kilbride Station (52.7 km^2), and since 1981 at the Mount Pearl Station (16.6 km^2) and near the Donovans Industrial Park Station (11.4 km^2). Later two stations were installed to monitor the effects of urbanization on the hydrologic regime from areas with differing degree of urbanization and land type usage. There are seven raingauges of which two are recording type, one at the Canada Department of Agriculture (CDA) farm and the other in the Mount Pearl area (Fig.1). The recording raingauges at the CDA farm and in the Mount Pearl area have been operational since 1954 and 1980 respectively. Rainfall data used in the HYMO model for analysis of various storm events was obtained from the recording raingauge located at the CDA Farm.

Land Use

The land use changes due to urban development have increased from 12% in 1974 to 17% in 1981. Although insignificant in the study area, the land use changes need careful consideration because they influence the runoff generating process in a complex and not easily discernable manner. However, due to the inherent complexities and lack of quantitative analysis defining the influence of land use on storm runoff volumes, its effects are analyzed by including them in the calculation of runoff curve numbers through the land use impermeability classification criteria of the United States Soil Conservation Service (SCS, 1972).

DESCRIPTION OF THE MODEL SETUP FOR THE STUDY AREA

The transformation of precipitation into streamflow hydrographs in the HYMO model is accomplished through the use of a synthetic unit hydrograph technique, the U.S. Soil Conservation Service rainfall-runoff relationships (SCS, 1972), and channel and reservoir routing techniques (Williams & Hann, 1973).

For simulation of the hydrologic response of the study area and to obtain flow estimates at various locations along the Waterford River and its major tributary, the study area was sub-divided in homogeneous hydrological units.

Discretization of the Study Area

The discretization of the study area into sub-basins, or hydrologic units (HU), was based on examination and interpretation of available 1:1250 and 1:2500 scale maps, air photos and field surveys and on the criteria that the minimum area of a sub-basin for HYMO application should not be less than 2.6 km^2 (Williams & Hann, 1972). The study area was divided into 23 hydrologic units. Twelve channel routing reaches as shown in Fig.1 were used. The input requirements for hydrograph routing through a channel in the HYMO model are the discharge/storage relationship for the channel characteristics.

A schematic representation of hydrologic units, river routing reaches and one reservoir routing used in the HYMO model for the study area is shown in Fig.1.

Model Parameters and Sensitivity Analysis

The HYMO model was calibrated and verified in the manner described elsewhere by the Hydrologic Modelling Group (1985) using eight storm events from the year 1981. All the events correspond to either antecedent moisture condition, AMC-I or AMC-III. No significant event corresponding to AMC-II was available. From test results of sensitivity analysis, it was found that peak flows are not very sensitive to variation in the values of the model parameters, the time to peak, t_p and recession constant K. Since runoff is directly related to parameter CN, the flow peaks are sensitive to variation in this parameter. On the average, a variation of ±1% in the value of CN was found to result in an increase or decrease of 4% in flow peaks.

EVALUATION OF THE IMPACTS OF URBANIZATION ON STREAMFLOWS

Impacts on Hydrograph Characteristics

The Waterford River Basin has a very thin soil overburden, thereby contributing to high runoff potential. That is, runoff characteristics of the Waterford River Basin are on such a higher potential that new urban developments do not appear to alter the runoff volumes of the basin. In other words, natural impervious conditions throughout the basin are so extensive that addition of artificially created impervious areas through urban developments neither significantly add to nor alter the already existing impervious conditions in the natural state of the basin. The implication is that the future urban developments in the basin, under normal circumstances, should neither add nor lead to significant alterations in the runoff generation potential of the basin. Occasionally, however, flood flows will be experienced within the basin due to other reasons such as severe rainfall storms and/or improved channel conveyance capacity resulting from channel modifications due to ongoing urban development. That is, floods in urban areas are not only caused by increase in impervious areas, but also by significant improvement in channel conveyance capacity.

Due to smoothing of land features and the addition of man-made drainage systems resulting from the urbanization process, it is expected that peak flows should increase without significant increase in the volume of direct runoff. Further, the urbanization process should decrease the time of concentration, especially in small basins with intensive urban development. From the results of hydrograph simulations, no changes in the time of concentrations could be discerned between 1974 and 1981. However, it must be realized that the amount of developed land only increased from 12% to 17% of the study area between the time period 1974 to 1981.

Impacts on Low and High Flows

For the assessment of the impact of urbanization on peak flows in the basin, two storm events that occurred in 1974 were selected for simulation using the calibrated model. The antecedent moisture condition for both events (August 28, 1974 and September 18, 1974) was determined to be AMC-I. There were no storm events satisfying the condition of AMC-III. The simulations were then carried out using the same model parameters as obtained in the calibration and validation phase for the storm events selected from the year 1981.

On one hand, it was observed that the peak flows at Kilbride were underestimated by 21% and the time to peak was two hours late for the event of August 28, 1974. This is exactly the opposite of what would be expected if significant urbanization had occurred. No comparison could be made for the Donovans and Mount Pearl, since streamflow gauges at these sites were not operational in 1974. On the other hand, the peak flows at Kilbride were overestimated by 10%, while the time to peak was one hour early for the event of September 18, 1974. Such types of changes in hydrograph characteristics are expected as a result of urbanization.

Since the results for both events are within the errors range encountered during the calibration/verification process, it is reasonable to stress that any urbanization which occurred between 1974 and 1981 has had no significant impact on high streamflows at Kilbride.

An assessment of available streamflow data at Kilbride station was also made to detect any change in streamflow characteristics caused by urbanization. For this purpose, the instantaneous peak flows, daily maximum flows, daily minimum flows and the annual flow volumes for the available historical records were examined with respect to independence, trend and randomness, Table 1.

TABLE 1 Statistical tests on each set of data carried out with NONPARA Package (Shiau & Condie, 1980).

Type of Flows	*Statistical Test*				
	Independence		*Trend*		*Randomness*
	(5%)	*(1%)*	*(5%)*	*(1%)*	*(5%)*
Instantaneous Peak Flows	*Yes*	*Yes*	*No*	*Yes*	*Yes*
Daily Maximum Flows	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Daily Minimum Flows	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Annual Flow Volumes	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*

In table 1, the presence of YES or NO below a particular level of significance for a specific test indicates whether or not the data possess the tested property. For example, for the annual flow volumes data set, YES entries below levels of significance in case of all the three tests indicate that the annual flow volumes from year to year can be treated as independent, random and free from any increasing or decreasing trend. It is apparent from the above table that all data sets can be treated at both levels of significance as independent, trend free and random with the single exception of instantaneous flows which cannot be considered trend free at 5% level of significance. In other words, within the limits of adequacy of the test results, there is no statistical evidence to suggest that streamflow characteristics in terms of instantaneous peak flows, daily maximum flow, daily minimum flow, and annual flow volumes are either increasing or decreasing at the Kilbride Station. A similar assessment of flow characteristics at Kilbride station was also concluded by the Hydrologic Modelling Group (1984) based on graphical analysis of some of the above noted flow data sets.

IMPACTS OF URBAN DEVELOPMENT SCENARIOS ON STREAMFLOWS

An evaluation of the effect of various development scenarios on peak flows in the Waterford River Basin was conducted by varying the time to peak, recession characteristics, direct runoff rates and volumes in the HYMO model. In order to simulate adequately the future conditions in the watershed, the curve number (CN), the time to peak constant (t_p) and the recession constant (K) for each hydrologic unit were modified in accordance with the projected level of urbanisation.

The average value of CN for AMC III is 95 in the calibrated and validated model using storm events from the year 1981. The high value of CN signifies the presence of relatively thin and impermeable overburden materials and exposed bedrock conditions in the watershed. In order to reflect any development in the watershed, this average value of CN would have to be increased so that the new average value of CN would be in the range between 95 and 100. The range variation for the value of CN is then very constrained to the point that the examination of detailed development scenarios cannot be justified.

For reasons explained elsewhere (Hydrologic Modelling Group, 1984), only one development scenario was examined using the level of urbanization that occurred during 1974-81 as evident from the results of the land use study. Assuming that the presently observed level of urbanization will continue in the future, the estimated average value of CN for the year 1991 would be 97. This represents a 2% increase in average value of CN as compared to the CN value for the calibrated and validated model based on storm events from the year 1981.

The other parameters for which the values were modified were the time to peak (t_p) and the recessions constants (K). The values for these parameters were somewhat arbitrarily reduced in accordance with the projected land use changes in each hydrologic unit. For some of the hydrologic units, they have been reduced by 25 percent, for others 15 percent, and for a few they were left unchanged.

Simulation of direct runoff was then undertaken assuming that a 12 hour storm rainfall would still produce the highest peak. Compared to 20-year return period flows of 11.5 $m^3 s^{-1}$, 19.9 $m^3 s^{-1}$ and 64.6 $m^3 s^{-1}$ for present conditions, the peak flows are estimated for the development scenario to be 14.1 $m^3 s^{-1}$, 23.6 $m^3 s^{-1}$ and 74.0 $m^3 s^{-1}$ at Donovans, Mount Pearl and Kilbride stations. The 100-year peak flows are 17.7 $m^3 s^{-1}$, 29.5 $m^3 s^{-1}$ and 93.3 $m^3 s^{-1}$ for Donovans, Mount Pearl and Kilbride, respectively compared to presently observed peak flows of 14.7 $m^3 s^{-1}$, 25.3 $m^3 s^{-1}$ and 81.5 $m^3 s^{-1}$ at these stations. The increase in peak flows vary from 14 percent at Kilbride to 23 percent at

Donovans. The increases are largely related to the stated arbitrary reductions in the time to peak parameter.

CONCLUSIONS

1. No discernable change in time to peak flow period was detected between 1974 and 1981, although the urban development has increased from 12% in 1974 to 17% in 1981.

2. Statistical tests suggest no discernable change in flow characteristics such as instantaneous peak flow, daily maximum flow, daily minimum flow or annual flow volume are either increasing or decreasing due to ongoing urbanization in the basin.

3. Changes in streamflow characteristics caused by urbanization, especially the percent increase in impervious areas, is not a significant factor in the basin, but other changes caused by urbanization such as increase in channel conveyance capacity should influence peak flows.

4. An increase in peak flows of the order of 10% at Kilbride and 20% at Donovans can be expected when the basin is fully urbanised, primarily as a result of improvement in channel conveyance capacity.

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Soil erosion research in the upper Wilmot River basin, P.E.I.

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ABSTRACT Soil erosion in summer crop lands in P.E.I. is predominantly due to snowmelt and/or light rainfall during the cool season of fall to spring. Potatoes are a major crop in P.E.I. and lands left bare following harvesting in early fall are subject to severe rilling and accompanying soil loss. Tourism is also a major industry and soil lost off farmland and deposited in the many estuaries is deleterious to aesthetics as well as recreational enjoyment of these natural facilities.

A program of soil erosion research started in 1984 under the Canada/P.E.I. Agri-Food Development Subsidiary Agreement has concentrated on the central potato-growing region of the province. A hierarchy of approaches has been developed encompassing microscale interrill soil loss measurements from frozen soils under a laboratory rainfall simulator, development of a field rainfall simulator for cool season field interrill measurements, and set-out of unit soil erosion plots in three monitored sub-watershed in the IWD monitored upper Wilmot River in central P.E.I.

RÉSUMÉ La fonte des neiges et/ou la pluie légère pendant la saison frais de l'automne au printemps sont les raisons fondement de l'érosion du sol sur les terrains cultivées en été à l'I.P.E. Le pommes de terre est une culture importante à l'I.P.E. et après la récolte, au début de l'automne, il ne reste plus de couverture végétale sur les champs. Par conséquent, la formation des rigoles et donc la perte du sol est rigoureux. La tourisme est un secteur aussi important que l'agriculture et le sol, perdu du terrain des fermes et déposé aux multitudes des estuaires est nuisible esthétiquement et il diminue la jouissance de celles facilités naturelles.

Une programme de recherche, commencé à 1984 entre le Canada et l'I.P.E., titulé "Agri-Food Development Subsiduary Agreement" avait concentré sur la zone central de culture de la pommes de terre de la province. On a développé une hiérarchie des approches qui encercle: (1) utilisant une simulateur de précipitation de la pluie au laboratoire, on a fait les mesurages micro-échelle de sol perte entre les rigoles des sols gelé, (2) pour etudier l'érosion entre les rigoles au champ pendant la saison frais, on a développé une simulateur de précipitation de la pluie et (3) on a etabli des parcelles d'érosion de sol a trois sous-bassins hydrographiques vérifié, qui se trouvent dans la région (vérifié par le D.G.E.I.) du cours supérieur de la rivière Wilmot.

INTRODUCTION

The Province of Prince Edward Island experiences a maritime climate in which temperatures generally fluctuate above and below freezing during the period of

November to April. As a result, periods of snow accumulation are interspersed with periods in which snowmelt often is accelerated by accompanying mist or light rainfall.

The principal crop in P.E.I. is potatoes which are grown in much of the central region on soils ranging from sandy loam to sandy. During summer the soils tend to vary from moist to dry and are well protected by the growing crops. Unlike the interior, summer rainfall is seldom of high intensity and summer runoff peaks and soil losses tend to be low. However, following potato harvesting in the period of mid-September (early varieties) to mid-October (late varieties), through until a reasonable cover has again been established by the succeeding crop, planted in late April to mid-May, soils left bare are vulnerable to high runoff rates with consequent substantial soil losses. Cold winter temperatures create frozen layers of low permeability in the soil, while periodic snowmelt periods and light rainfall saturate the surface soil. Particularly during the latter part of winter and early spring, soils tend to be 'soupy', considerable ponding occurs on lands, and streams are discoloured for several days. A major portion of the annual soil erosion losses and thereby estuary deposition clearly occurs during this period.

A comprehensive program aimed at evaluation of alternate land use practices to protect soils during the 'cool' season started in 1984 under the Canada/P.E.I. Agri-Food Development Subsidiary Agreement. Initial tests involved the use of a laboratory rainfall simulator to evaluate interrill erosion on typical selected soils, with and without a viable winter cover crop and under frozen and summer temperature soil conditions. A single nozzle rainfall simulator comprising twin units was specifically designed and constructed to extend interrill studies to the winter field situation.

A second, and more detailed set of laboratory tests in 1986 accompanied an extension of the project work through a hierarchy of field installation of unit erosion plots and small watershed monitoring and modelling within the IWD monitored upper 35 km^2 Wilmot River watershed in the potato production areas of central P.E.I.

Each of these facets of microscale laboratory work through to sub-watershed monitoring is presented below.

LABORATORY INTERRILL EROSION STUDIES

A laboratory rainfall simulator in a temperature-controlled enclosure at Technical University of Nova Scotia was used to test the effects of various treatments on resulting volume and mass sediment in splash and runoff from selected typical and diverse P.E.I. soils. Seventy-two soil boxes, each measuring 914 mm in plan and 325 mm deep, were constructed and used in a factorial experiment comprising three soils (Dunstaffnage sandy loam, Charlottetown fine sandy loam and Dunblane loam), two temperature treatments (frozen and room temperature), three cover treatments (bare, early seeded and late seeded winter rye) and two erosivity effects (rainfall alone at 50 $mm\ h^{-1}$ and rainfall plus added upslope flow equivalent to 150 $mm\ h^{-1}$). All tests were run for 30 minutes at a slope of 5 percent. During a rainfall simulator run a frame was placed over each of the four soil boxes tested at one time. Troughs, which ran down the inner sides and across the upslope end of each frame enable collection of splash samples.

The volume of splash collected was not significantly affected by any of the treatments, and only cover affected the amount of sediment in the splash. Sediment splashed from a bare soil surface was approximately twice that from late seeded winter rye and three times that from early seeded, and therefore more developed, winter rye. Volume of runoff was significantly affected by the types of soil and erosivity application, while sediment mass was significantly affected by each of the treatment effects. The least soil loss occurred on early seeded, unfrozen, loam soil subjected to rainfall alone.

A follow-up study was carried out in 1986/87 in which the previously developed facilities were utilized for a greater in-depth evaluation of the major environmental, soil and crop factors which influence soil loss on P.E.I. Seventy-two additional soil boxes were constructed, and all 144 boxes were then used in a factorial experiment comprising three soils (Dunstaffnage sandy loam, Charlottetown fine sandy loam and Tignish loam), two temperature treatments (continuously frozen and five freeze-thaw cycles ovar a 10-day period), three cover treatments (bare, early seeded winter rye and cereal residue incorporation) and two layering effects (homogeneous and an induced compacted layer at 150 mm depth). Simulated rainfall alone was applied to all boxes at a rate of 50 mm h^{-1} for 30 minutes. Slope was 5 percent. The four replications were run in two sequential randomised blocks over the course of the winter. Soil boxes not yet subjected to freezing treatment and testing remained outdoors.

Statistical analyses indicated a slight but not significant decrease in runoff volume and an accompanying increase in soil loss with time over the winter. Soil loss was similar on each of the three soils. In terms of cover, cereal residue produced the least overall soil loss followed by rye cover. Continuous freezing produced a greater runoff and soil loss than freeze-thaw cycling although sediment concentration was unaffected. The presence of a compact layer did not affect runoff but increased soil loss.

Size distributions, by wet sieve analysis, were determined for the sediment fractions and for the original soils. Sediment was markedly enriched as compared to the original soils.

FIELD RAINFALL SIMULATOR

A single-nozzle downward spraying field rainfall simulator was designed and constructed for field use on frozen soils.

The nozzle is located centrally within a frame having four telescoping legs which straddle a 1 m^2 plot. Nozzles are interchangeable and current nozzles apply simulated rainfall at rates of 35, 70 and 300 mm h^{-1}. Runoff is collected by suction from a washboard shaped collection section.

EROSION PLOTS

Three sets of erosion plots have been laid out, since the fall of 1986, one set in each of three watersheds within the upper Wilmot River basin in central P.E.I. Each set comprises three unit plots of 22.1 m in length and 4 m in width, the former dimension conforming to the standard length of a unit erosion plot and the latter selected to facilitate ease of operation with farm machinery.

Runoff at the lower end of each plot is concentrated by a washboard section and then flows through a short length of channel into a below-ground heated bunker. The channel section terminates in a HS flume through which the flow falls into the first of a sequence of three barrels. One-seventh of the overflow from the first barrel flows into a second barrel and one-ninth of the overflow from this barrel flows into a third barrel. The capacity of the first barrel represents an equivalent of 2 mm of runoff, the second barrel 18 mm and all three barrels together represent 170 mm of runoff. Runoff and sediment are measured year-round on an event, or daily sequence of events, basis. Stage recorders and automatic sediment samplers are being constructed for installation at the HS flume outflow of each plot.

Data are recorded on a datalogger at each site and variously comprises precipitation, soil moisture, soil temperature, air temperature, wind travel, evaporation pan level and stage levels in a flume in the associated watershed outflow channel.

At each site, one of the plots was planted to barley in summer, 1987, while the remaining two plots were planted to early maturing potatoes and late maturing potatoes, respectively. Following harvest in fall, barley stubble was left standing in the first plot, the plot with early maturing potatoes was planted to winter rye and the remaining plot was left bare over winter.

WATERSHEDS

As indicate above, each set of erosion plots is adjacent to the outflow of a sub-watershed within the IWD monitored upper Wilmot River basin. The three watersheds comprise 360 ha of mixed (predominantly pasture) land-use, 260 ha of partly potato lands and 140 ha of predominantly potato lands.

A Parshall flume was installed in the stream in each of these locations in spring 1987. Water levels are recorded on the datalogger at each site.

CONCLUSIONS

Although soil erosion rates in excess of 40 Mg ha^{-1} have been measured on P.E.I. potato lands, little direct research on viable means to control these losses has occurred. The low USLE erosivity (R) value of 900 MJ mm ha^{-1} h^{-1} y^{-1} projected from rainfall data along, considerably underestimates the soil losses which occur primarily during the snowmelt period of late March and early April.

Cropping practices, climate and soils in P.E.I. create an environment which is unlike that of the continental interior and requires emphasis which therefore differ. Major effort over the past year has been placed in developing the field facilities described above, and which provide a mutually beneficial research facility for graduate studies. It is hoped that national funding agencies will recognize (a) the need to support soil erosion studies in the Atlantic Region, and (b) that technology developed outside is not directly transposable or indeed necessarily applicable in this region.

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Effects of development on erosion and sedimentation in the Halifax Urban Watersheds Program

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ABSTRACT Urban development within the Halifax Urban Watersheds has introduced changes in land use that cause severe erosion and sedimentation problems. Development sites within the Halifax Urban Watersheds were monitored over a period of 17 months for the use of erosion and sedimentation control measures. Information obtained from this monitoring was used to evaluate the effectiveness of the control measures adopted at the sites.

Surface stabilization by means of hydroseeding, sodding, gravelling, and paving were found to have varying degrees of effectiveness as erosion control measures, depending on the percent of exposed area stabilized. The use of diversion ditches as a method of erosion control was ineffective. Straw and crushed aggregate filters and sedimentation ponds were ineffective as sedimentation control measures. "Enviro-fence" (silt fence) was an effective sedimentation control measure when initially installed and subjected to low loadings, but became ineffective under prolonged and increased loading conditions.

Study results indicate that site-specific erosion control measures should be adopted as a first line of defence against erosion and sedimentation. For both erosion and sedimentation control measures, routine monitoring and maintenance are vital to ensuring control measures work effectively.

RÉSUMÉ Les changements d'utilisation des terres suite à l'urbanisation des Bassins Urbains d'Halifax ont causé de graves problèmes d'érosion et de sédimentation. Des méthodes de contrôle de l'érosion et de la sédimentation ont été appliquées à des sites en développement dans ces bassins. L'effet de ces méthodes a été suivi pendant 17 mois, et leur efficacité a été évaluée.

Le taux de succès obtenus suite à la stabilisation de la surface par pulvérisation d'un stabilisant contenant des semences, par la pose de gazon, par l'épandage de gravier et par le pavage dépendait de la proportion de la surface exposée qui était stabilisée. Les fossés de diversion se sont avérés inefficace contre l'érosion, et la sédimentation n'a pas été réduite par les filtres de paille et d'agrégrats broyés, ni par les étangs de sédimentation. L'"Enviro-fence", une barrière à limons, a réduit efficacement la sédimentation après son installation et sous de faibles charges de sédiments, mais est devenue inefficace après une utilisation prolongée et des charges en sédiments plus fortes.

L'étude indique que des méthodes de contrôle d'érosion, spécifiques au site, devraient être la première ligne de défense contre l'érosion et la sédimentation. De plus, l'efficacité continue de toute mesure de contrôle dépend d'une surveillance et d'un entretien constant.

INTRODUCTION

In May, 1977, the City of Halifax changed its water supply source from the Chain Lakes and Long Lake to Pockwock Lake. This change in water supply resulted in the designation of the Chain Lakes as Halifax's back-up water supply and the release of Long Lake to development. The Chain Lakes and watershed lands were to remain protected from development, while the Long Lake watershed lands were purchased by the Province of Nova Scotia to be managed by the Provincial Department of Lands and Forests as a Provincial Park. Pressure for development within the Chain Lakes and Long Lake watersheds have been strong and both lakes are currently threatened by on-going developments.

From April 1, 1985 to August 25, 1986, seven development sites within the Chain Lakes and Long Lake watersheds of Halifax were monitored for the use of erosion and sedimentation control measures. Following is a general description of five of the seven development sites where significant activity occurred and control measures were adopted.

The Atlantic Winter Fair Exhibition Park site occupies a 26 ha area within the Long Lake watershed. The site overlies a drumlin containing a high percentage of fine clay material, making the site highly susceptible to erosion and sedimentation.

The Bayers Lake Industrial Park site covers a 200 ha area having a total drainage area of approximately 300 ha contained within six watershed areas. During the study period, development activity was confined to three watersheds: Second Chain Lake, Long Lake, and Bayers Lake. The park overlies an area of shallow bedrock and is characterized by several swamps and outcrops. Depth of overburden is less than 1.0 m in most areas. These conditions minimize the potential for erosion and sedimentation from the site.

The Ragged Lake Research and Business Park covers a 485 ha area and is contained within three watersheds: Long Lake, Ragged Lake, and Blueberry Pond. The park overlies a drumlin containing a high percentage of fine clay material and depth of overburden varies from zero to greater than 1.5 m. These conditions, similar to those at the Atlantic Winter Fair site, make the site susceptible to erosion and sedimentation.

The Department of Transportation Storage Facility was completed in 1984. During the study period, work was carried out to reconstruct and expand a parking lot at the front of the site. Runoff from the parking lot construction area, as well as the facility site, enters Long Lake.

The Bayers Brook Diversion Dam and Channel was part of a master drainage plan to control and manage surface runoff from those areas of the Bayers Lake Industrial Park within the Chain Lakes watershed. The diversion dam was constructed immediately west of Second Chain Lake and the diversion channel was installed immediately north of Long Lake to carry Bayers Brook into Long Lake and protect the Chain Lakes.

Five types of control measures were adopted at the various development sites and these measures may be classified as either erosion control measures or sedimentation control measures. Erosion control measures consisted of: (1) surface stabilization (i.e. hydroseeding, sodding, gravelling and paving), (2) ditching of storm runoff, while sedimentation control measures took the form of (3) straw and crushed aggregate filters, (4) sedimentation ponds, and (5) "enviro-fence" (silt fences).

(1) Surface stabilization techniques were found to be effective but the degree of effectiveness depended on the percent of exposed area stabilized. Sodding and paving were most effective because they provided a 100% cover. Gravelling was less effective because gravel covers were subject to disturbance by vehicle activity and also because the gravel tended to wash away under high runoff

conditions. Hydroseeding was also less effective due to the time factor required for growth and deficiencies in hydroseed application.

(2) Ditching of storm runoff to control erosion was ineffective because the ditches themselves were unstable. At all three sites where ditches were constructed, the ditches were not properly stabilized and suffered erosion to varying degrees. At one site, "treated" runoff from a sedimentation pond flowed along an unstabilized ditch and picked up more solids before leaving the site.

(3) Straw and crushed aggregate filters were ineffective for reducing the total suspended solids concentration in site runoff, even under low sediment loadings. Four of the seven filters washed out to some extent during high flow conditions. The filters were found to be unsuitable for high flow/high loading conditions and were ineffective under low flow/low loading conditions because they were not securely installed nor properly maintained.

(4) Sedimentation ponds were found to be ineffective for reducing the total suspended solids concentration in site runoff. The ponds were ineffective due to poor design and lack of suitability for site conditions. The ponds were often subjected to high loadings of fine suspended solid material and could not provide the high retention times needed for settling.

(5) "Enviro-fence" (silt fences) had varying degrees of effectiveness depending on how they were installed and the flow conditions to which they were subjected. When properly secured and operated under "moderate" flow conditions (i.e. not overflowing) the silt fences were found to be effective. However, this effectiveness was only temporary because silt was allowed to build up on the fences, reducing their filtering capacity and resulting in "untreated" water overflowing the fences. High flow conditions alone also caused overflowing as well as undermining of the silt fences.

In conclusion, there is a vital need for more planning prior to the selection and implementation of erosion and sedimentation control measures, so that control measures are site specific. In addition to planning for site specific control measures, "managers" as well as "installers" and "regulators" must be trained to promote the use of construction practices and erosion control measures that minimize the duration and area of soil exposure and effectively control surface runoff to prevent erosion at the source. Sedimentation control measures often prove ineffective, especially for sites characterized by fine soil materials. Monitoring and maintenance programs must also be implemented to ensure effective control measures continue to work effectively and ineffective control measures are replaced to effective control measures.

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Numerical modelling techniques in the Halifax urban watersheds program

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ABSTRACT The Halifax urban watershed program was established in 1981 to investigate impacts of urbanization on previously undeveloped watershed-lake ecosystems. The research program has been extended to consider effects of acidification in these systems. Mathematical models of watersheds and lake systems are recognized as an important facet of the research programs. System data can be used for model calibration, verification, and development; and can supplement data collection programs. QUALYMMO, a continuous simulation watershed model, has been the subject to two completed Master's theses projects. A follow-up project forms the basis for a current undergraduate thesis, which will lead into further exploration of the model's capabilities, limitations, and applications to the program, and to appropriate model development. Preliminary modelling studies have been carried out in two other subject areas: a simple finite difference groundwater model was developed to represent a watershed-lake system, and first steps have been taken toward development of a three-dimensional water quality model applicable to small lakes.

RÉSUMÉ Le programme des bassins urbains de Halifax a été mis sur pied en 1981 afin d'étudier l'impact de l'urbanisation sur des écosystèmes bassins-lacs jusque là non-développés. Le programme de recherche comporte aussi maintenant un volet sur l'impact de l'acidification sur ces systèmes. La modélisation mathématique de ces systèmes bassins-lacs est vue comme une facette importante du programme. Les données des systèmes bassins-lacs peuvent servir au développement, à la vérification et au calage de modèles, et peuvent suppléer aux programmes de récolte de données. Le simulateur de bassins en continu, QUALYMMO, a fait l'objet de deux projets de maîtrise maintenant terminés. Faisant suite à ces études, une thèse de baccalauréat devrait mener à une exploration renouvelée des possibilités, des limites et des applications du modèle, ainsi qu'à un effort de développement approprié. Des études préliminaires de modélisation ont déjà été effectuées dans deux secteurs de recherche différents: un modèle simple de l'eau souterraine par différences finies a été développé afin de représenter un système bassin-lac, et le travail a débuté sur un modèle tri-dimensionnel de qualité des eaux qui serait applicable à de petits lacs.

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Results of hydrometeorological studies in the Nashwaak experimental watershed project, New Brunswick

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ABSTRACT In this paired-basin experiment, clear-cutting of one of the basins was carried out in 1978 following a seven year calibration period. Observed hydrometeorologic effects are presented with respect to the following: (1) Energy Balance: albedo in the clear-cut basin decreased in the first year after cutting, but within three years increased to levels about 4% higher than before. Nine years after cutting albedoes are still about 2.5% higher than before. (2) Snow Cover: there had been a negative correlation of snow cover with canopy closure, and a positive relationship with elevation; after clear-cutting the relationship with elevation reversed and basin-wide snow cover was depleted by the transport and evaporation of blowing snow. (3) Streamflow: in the first year following clear-cutting annual yield of the clear-cut basin was increased by 241 mm. Recovery is estimated to require 14 years. Summer flow was increased by 134 mm in the first year following clear-cutting and low flows were more than doubled. After clear-cutting there was usually a desynchronization of snowmelt runoff between the two basins, with peak flow from the clear-cut basin advanced by as much as 44 days.

RÉSUMÉ En 1978, après sept ans d'étalonnage, l'un des bassins d'une étude par bassins jumelés a été coupé à blanc. Les effets hydrométéorologiques suivants sont présentés. (1) Bilan énergétique: l'albédo du bassin coupé a diminué l'année de la coupe, mais, en dedans de trois ans, a augmenté à des niveaux de 4% supérieurs aux niveaux antérieurs. Neuf ans après la coupe, l'albédo est encore 2.5% plus élevé qu'avant. (2) La neige: Avant la coupe, le couvert neigeux variait directement avec l'élévation et inversement aves la fermeture des cimes; après la coupe, la relation avec l'élévation s'est inversée, et le couvert du bassin a été réduit à cause du transport de la neige, et de son évaporation pendant ce transport. (3) Débits: Au cours de l'année suivant la coupe, le débit annuel du bassin traité a augmenté de 24 mm. Nous estimons que le retour à la normale prendra 15 ans. Les débits d'été ont été accrus de 134 mm le premier été, et les débits d'étiage ont presque doublés. Depuis la coupe, les débits de fonte des deux bassins sont désynchronisés; les débits de pointe du bassin coupé sont avancés de jusqu'à 44 jours.

INTRODUCTION

A paired-basin experiment was carried out in central New Brunswick to study the effects of clear-cutting. The study area is in a region where annual precipitation averages 1280 mm and is evenly distributed by season. A snowpack usually lasts from mid-December to early May, reaching a maximum water equivalent of about 250 mm. Mean annual temperature is about 3°C. The basins are large, with areas of 391 ha for the treatment basin (Narrows

Mountain Brook) and 660 ha for the control (Hayden Brook). Elevations range from 195 to 478 m; average aspects are similar.

Originally the basins were completely forested with about equal proportions of tolerant hardwoods and evergreen softwoods. Hardwoods dominated the higher elevation areas, with a gradation through mixedwood cover to pure softwoods on the lower slopes. In 1978, after a seven-year calibration period, 94% of the forest cover was harvested from Narrows Mountain Brook basin. This paper summarizes some of the more significant treatment effects that have been observed during the past nine years.

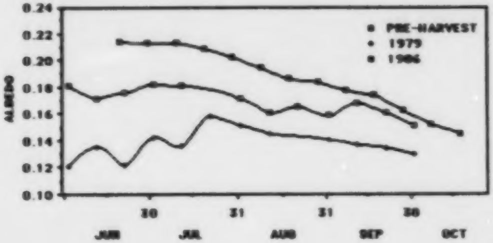


FIG.1 Summer-season variations in albedo for pre-harvest conditions, and one and eight years afterwards.

ENERGY BALANCE

A mean summer albedo of 0.161 was found prior to clear-cutting, decreasing steadily during the season from about 0.18 at the end of May to 0.15 at the beginning of October. Radiation measurements were continued for three summers following the clear-cutting, and after a three-year interruption were resumed from 1985-87.

Characteristic summer-season albedo curves before harvest, and one and eight years afterward, are shown in Fig.1. Albedo was reduced in the first year after clear-cutting. The second year, however, albedo had recovered to a level near that of the original forest and continued to rise for several years thereafter as new vegetation occupied the site. The progression of albedoes can be shown more clearly by using mean values from 20-day periods in mid-summer (Fig.2). The reduction immediately after harvest is followed by a rapid rise to about 0.22 in 1981. Albedoes were still near that value when observations resumed in 1985, but have lessened toward pre-clear-cut values since then.

SNOW COVER

Relationships between snow cover and topography and forest cover were established from snow survey data. A summary of the average individual effects at the time of maximum pack is given in Table 1. Slope and aspect were rarely significant at the time of maximum pack; aspect (N vs S) did become significant late in the season, with differences in depth reaching 10 cm.

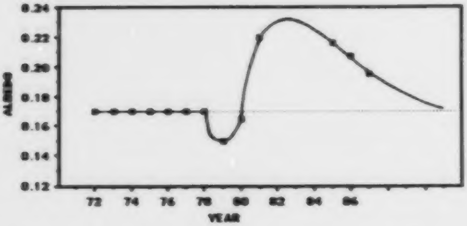


FIG.2 Mid-summer albedoes for pre-harvest conditons, and for the six post harvest years when radiation data have been collected. Values are means of 20-day periods.

TABLE 1 Effects of elevation and forest cover on snow depth and water equivalent.

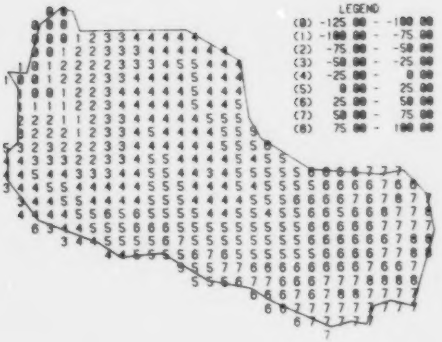
Basin Characteristic	*Snow Depth*	*Water Equivalent*
Elevation	*+6 cm/100 m*	*+20 mm/100 m*
Forest Cover	*+2 cm/10% decrease in canopy closure*	*+5 mm/10% decrease in canopy closure*

After clear-cutting coincident surveys were completed in both basins in 1980, 1981 and 1982. In the absence of forest cover, the positive relationship that had existed between snow cover and elevation showed a marked reversal. At the time of maximum pack, differences for each 100 m increase in elevation decreased by 9.0 cm and 16.7 mm for depth and water equivalent, respectively.

Basin-wide effects

When surveys were carried out in both basins, control-basin relationships were used to estimate the treatment basin depths and water equivalents that would have been observed if the forest were still there. Differences between "forested" and clear-cut snowpacks can then be shown in each hectare of the basin by using a grid-square mapping technique. Fig.3 shows the distribution of water equivalent differences for January 26, 1982. It can be noted that there are large deficiencies at the higher elevations with excesses throughout the lower elevation areas. This pattern developes early in the season and cannot be attributed to differential ablation, but rather indicates a substantial redistribution of snow from high- (exposed) areas to more sheltered low-elevation areas.

An examination of mean basin snow cover after clear-cutting (Fig.4) suggests that snow is being transported out of the basin, as well as being


LEGEND
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(1) -100 00 - -75 00
(2) -75 00 - -50 00
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(4) -25 00 - 0 00
(5) 0 00 - 25 00
(6) 25 00 - 50 00
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FIG.3 Distribution of snowpack water equivalent differences in each heactare of the clear-cut basin for January 26,1982. Values in the legend are mm.

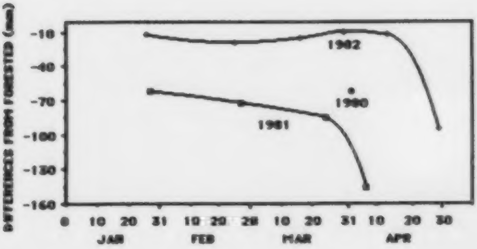

FIG.4 Seasonal deficiencies in mean basin water equivalent in 1980, 1981, and 1982.

redistributed within the basin. In all years total water equivalent is decreased - particularly in 1981 where the basin shows a 62 mm water equivalent deficiency by late January.

The effects of large openings on evaporation and transport of blowing snow has been the subject of extensive research in the mid-west, and a procedure for its estimation has been outlined in U.S. Forest Service (1980). This procedure has been adapted to Canadian conditions as part of the WRENSS model (R.H. Swanson, pers. comm., 1987). Using the WRENSS procedure, and including characteristics of winter climate and the basin, estimates of the amount of snow lost were calculated for each year since clear-cutting. Deficiencies in water available for streamflow as a result of blowing snow (according to WRENSS), and differences in snowpack water equivalent resulting from clear-cutting (according to late-March or early-April snow surveys) are shown in Table 2.

TABLE 2 Deficiencies in water available for streamflow (mm).

Year	*WRENSS*	*Snow Surveys*
1979	*179*	
1980	*75*	*62*
1981	*51*	*85*
1982	*36*	*15*
1983	*17*	
1984	*19*	
1985	*0 - effect permanently gone*	

STREAMFLOW

Annual flows

Regression of calibration-period annual flows produced equation (1) that can be used in estimating the effect of clear-cutting:

$$QNM = -66.82 + 1.005\ QHB + 1.293\ \Delta P \qquad (1)$$

$$(R = 0.98,\ S.E. = 35.67\ mm)$$

where QNM = annual streamflow, Narrows Mountain Brook (mm)
QHB = annual streamflow, Hayden Brook (mm)
ΔP = between-basin difference in precipitation (mm)

The shaded portions of the columns in Fig.5 show the effect of clear-cutting estimated by this equation. It would seem odd that the effect should increase steadily through the first four years after treatment if the results of snow surveys had not indicated that evaporation and transport of blowing snow represented losses to the basin water balance. When WRENSS estimates of the snowpack losses are added to the estimates from regression, total treatment effect is represented by the full height of the columns in Fig.5.

These data were used to derive equation (2) describing the effect of clear-cutting on annual flow in any year:

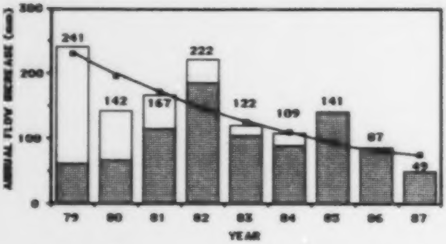

FIG.5 Effect of clear-cutting on annual yield.

$$\Delta Q = 270.97e^{-0.140\,(\mathrm{Year})} \tag{2}$$
$$(r = 0.84,\ \mathrm{S.E.} = 40.4\ \mathrm{mm})$$

where: ΔQ is the increase in annual flow (mm), and Year is years since clear-cutting.

The trace of (2) is added to Fig.5. If annual flows continue to recover at a rate described by (2), they will have returned to within the error of the calibration period relationship 14 years after clear-cutting.

Summer flows

Differences between precipitation and streamflow (P-Q) were calculated for each of the summer months June to September for both the calibration and post-treatment periods. In an attempt to compensate for storage effects between months, the precipitation associated with a month's streamflow included that which fell on the last day of the previous month, and excluded that which fell on the last day of the current month.

For each summer month, clear-cut- *versus* control-basin regression relationships of P-Q were determined for the calibration period. After clear-cutting, the deviation of each month's P-Q from that month's calibration-period regression were summed to give a within-year estimate of the effect of clear-cutting on summer flows. Fig.6 shows the effects each year since treatment. These data were used to derive equation (3) describing the effect:

$$\Delta Q = 98.49e^{-0.170\,(\mathrm{Year})} \tag{3}$$
$$(r = 0.70,\ \mathrm{S.E.} = 26.24\ \mathrm{mm})$$

Where: ΔQ is the increase in summer flow (mm), and Year is years since clear-cutting.

The trace of (3) is added to Fig.6. Because of the way in which was (3) calculated, the error of the calibration period relationships is not known, but 14 years after clear-cutting (recovery time for annual flows) the effect would be only 8.15 mm.

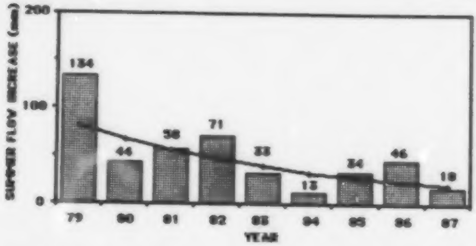

FIG.6 Effect of clear-cutting on summer flows.

Low flows

Outside of the winter "desert" period, lowest flows were observed in late summer – in either August or September with only one exception throughout the period of record. To study the effect of clear-cutting, low-flow durations were calculated for the months of August and September.

Low flows were defined as those exceeded 90% of the time, and the ratio of lowflow in the clear-cut basin to that in the control basin used to describe treatment effect. Ratios calculated in this way are plotted in Fig.7. These data were used to derive equation (4) describing the effect, and the trace of (4) is added to Fig.7:

$$\text{Ratio} = 2.073 \text{ year}^{-0.585} \qquad (4)$$
$$(r = 0.87,\ S.E. = 0.21)$$

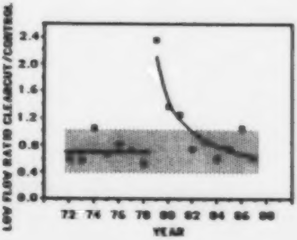

FIG.7 Effect of clear-cutting on summer low-flow ratios. Shaded area indicates the 95% interval around the pre-clear-cut mean of 0.70.

The effect of clear-cutting is obvious in the drastically increased ratios of 1979, but recovery is rapid in the fourth year after clear-cutting, low-flow ratios had returned to within the 95% confidence interval of the pre-clear-cutting data.

Desynchronization of peak flows

Throughout central New Brunswick annual peak flow often occurs as a result of a rainfall event added to snowmelt the case observed throughout this period of record. Prior to clear-cutting, peak flows in the control and clear-cut basins occurred on the same day; after clear-cutting the date of peak flow was the same for both basins in four out of nine years and desynchronized by up to 44 days for the others.

In the four years that were similar, the rainfall event associated with peak flow was sufficient to overcome differences in snowpack ripeness between the two basins. In the other years, advanced ripening and snowmelt contributions already adding to streamflow resulted in earlier peak flows from the clear-cut basin. Streamflows from March and April 1984 provide an excellent example (Fig.8). Flows from the clear-cut basin exceeded those from the control basin for the first four spikes on the hydrograph (March 18 and 23, April 6 and 17), but were less than those of the control basin thereafter.

SUMMARY

Clear-cutting a 391 ha basin in central New Brunswick resulted in many hydrological effects. Nine years later, recovery is well advanced, but most effects are still detectable.

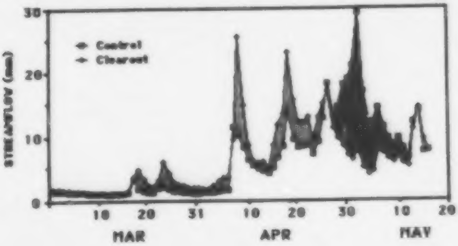

FIG.8 Hydrographs of the clear-cut- and control-basins for March and April, 1984.

Rapid recovery would be expected in this region because re-establishment of forest cover begins the year after the harvest is completed. Clear-cuts are quickly invaded by intolerant pioneer species and the tolerant hardwoods regenerate vegetatively from stump sprouts and/or root suckers. Under optimum conditions these species may show height growths up to one metre per year with rapid development of leaf area.

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CANADIAN HYDROLOGY SYMPOSIUM (CHS:88)
ASSOCIATE COMMITTEE ON HYDROLOGY
NATIONAL RESEARCH COUNCIL OF CANADA
MAY 9-11, 1988
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Snowmelt runoff modelling in the Lac Laflamme basin[1]

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ABSTRACT The variable source area model of stormflow generation VSAS2 has been adapted to simulate snowmelt runoff in the Lac Laflamme forested basin, 80 km north of Quebec City. The model has been transformed to accept different water inputs according to topography, to factor the effect of lake water storage in the discharge hydrograph and to utilize three months worth of hourly snowmelt data (simulated with the SNOW-17 model). The explicit form of flow equations included in VSAS2 has also been transformed to use an iterative approach. Results showed that low flows in early spring were well reproduced by the variable source area concept. However, all seasonal peak flows were strongly underestimated when all water input was considered to infiltrate. In each field season (1985, 1986 and 1987), high peak flows were generated through an extensive turbulent flow network on the basin. Observations on the site showed that the natural topographical drainage network was augmented in the spring by superficial concrete frost, pipe throughflow at the organic-mineral soil interface and snowpack basal ice layers. It was therefore necessary to use an infiltrability index to improve the model. The relative proportion of bare ground to snow covered areas was related to the rising of streamflow hydrographs. Thus, values of snow cover areal extent were used as an index to the prevailing conditions of soil infiltrability on the basin. With such an infiltrability index, results from VSAS2 were greatly improved, supporting the hypothesis of an important surface flow contribution during snowmelt.

RÉSUMÉ Le modèle à sources variables d'écoulement VSAS2 a été adapté pour simuler l'écoulement de fonte dans le bassin boisé du Lac Laflamme, situé à 80 km au nord de Québec. Le modèle fut transformé pour accepter différents apports d'eau en relation aven la topographie, pour tenir compte de l'effet du stockage d'eau dans le lac sur l'hydrogramme et pour utiliser des données de fonte horaires s'étendant sur trois mois (simulées par le modèle SNOW-17). La forme explicite des équations d'écoulement incluses dans VSAS2 a également été transformée pour utiliser une approche itérative. Dans l'ensemble, les résultats ont montré que les écoulements de base en début de printemps étaient

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[1] This study was conducted while the authors were working at the Laboratoire d'Hydrologie Forestière and at the Centre de Recherche en Biologie Forestière, Faculté de Foresterie et Géodésie, Université Laval, Québec, Canada G1K 7P4

bien reproduits par le concept des sources variables de l'écoulement. Toutefois, toutes les pointes saisonnières furent grandement sous-estimées lorsque le modèle considérait que tous les apports d'eau s'infiltraient. Pour chaque saison à l'etude (1985, 1986, et 1987), les fortes crues correspondaient au développement d'un réseau d'écoulement turbulent sur l'ensemble du bassin. Des observations sur le site ont montré que le réseau naturel de drainage était amplifié au printemps par un gel superficiel de type compact, de l'écoulement en conduit à l'interface de la matière organique et du sol minéral et une couche de glace à la base du couvert de neige. Il devenait donc nécessaire d'utiliser un indice d'infiltrabilité pour améliorer le modèle. La fraction de sol déneigé était corrélé à la montée de l'hydrogramme d'écoulement. Ainsi, les valeurs de pourcentage de recouvrement du sol par la neige furent utilisées comme indice des conditions d'infiltrabilité du sol prévalant sur le bassin. Avec un tel indice d'infiltrabilité, les résultats de VSAS2 furent grandement améliorés, ce qui supporte l'hypothèse d'une contribution importante de l'écoulement de surface au printemps.

INTRODUCTION

This study is part of a research program on the impact of atmospheric pollutants on forest ecosystems. It aims to improve our understanding of the flow processes in the Lac Laflamme forested basin during snowmelt. In order to identify the various mechanisms involved in the snowmelt runoff, a physically based model was applied for springs 1985, 1986 and 1987. It was known that the Hortonian concept of streamflow generation could be valid for snowmelt runoff from frozen basins (Freeze, 1972). Observations on the Lac Laflamme site from 1985 to 1987, and a previous study (Roberge & Plamondon, 1987) had revealed that during snowmelt, production of runoff was related to the occurrence of an ephemeral and variable streamflow network associated with the rising of the water table to the soil surface. This close relation between groundwater level and surface flow is a clear illustration of the variable source area concept (VSAC). Thus, it was expected that the snowmelt streamflow regime of the Lac Laflamme basin should be well represented by a model based on this concept. Since it is also based on physical processes, the VSAS2 model (Bernier, 1985) was selected. The model has been transformed to accept different water inputs according to topography, to factor the effect of lake water storage in the discharge hydrograph and to utilize three months worth of hourly data. To ensure convergence of the solution, the explicit form of flow equations included in VSAS2 was transformed to use an iterative approach. VSAS2 had never been tested for a laurentidian headwater basin and results obtained with a modified version are presented here.

DESCRIPTION OF THE SITE

The study site is the Lac Laflamme experimental basin, located in Forêt Montmorency (47°N, 71°W), 80 km north of Quebec City (Fig.1). The climate is characterized by a high annual precipitation (1,400 mm), of which more than one third falls as now. The first order Lac Laflamme basin is covered by a balsam fir - white birch forest type. The stand consists of 80% balsam fir (*Abies balsamea* (L) Mill.). The forest is 50-70 years old. The basin has a total area of 68 ha, of which 6 ha are occupied by the lake. Slopes vary from 0 to 30% (Fig.1).

The Lac Laflamme is fed by groundwater, with small creeks contributing during snowmelt. The average permeability of the deep deposits has been

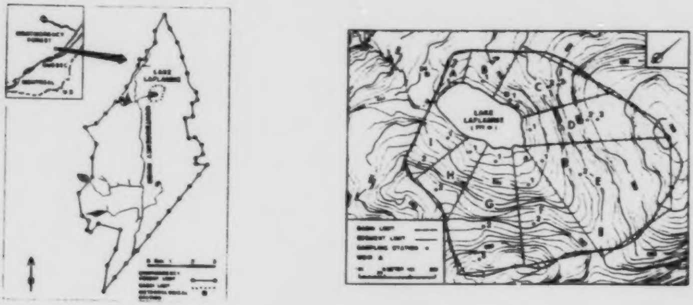

FIG.1 Location map of the Forêt Montmorency and topography of the Lac Laflamme basin.

estimated at 15 cm h^{-1} (Bernier *et al.*, 1983) and the mean residence time for lake water is around two months. The instantaneous discharge from the lake varied from 0.003 to 0.794 m^3 s^{-1}, for the 1985 to 1987 period. Surficial deposits are sandy tills varying in depth from 0.5 m in the upper slopes to 15 m under the lake. The soil has an organic layer (MOR) 5 to 15 cm thick. The 0-50 cm layer has a very high saturated hydraulic conductivity (20-60 cm h^{-1}).

On the Lac Laflamme basin, a turbulent streamflow network is present during the melting period. This flow network may result from two different phenomena. The first is the possible partial and intermittent concrete freezing of the soil surface, which decreases its hydraulic conductivity. The second is the complete saturation of the soil profile producing exfiltration zones and pipe throughflow. These phenomena have only received little attention for laurentidian balsam fir forest systems, but both have been observed at Lac Laflamme.

The maximum soil freezing depth does not exceed about 40 to 60 cm in the Lac Laflamme basin (Prévost *et al.*, 1988). Because of its high permeability, the soil is not saturated at the onset of freezing in November. Even if concrete frost rarely appears in forest soils (Pierce *et al.*, 1958), the particular conditions encountered on the site may cause meltwater to freeze at the top of the soil profile, thus producing surface water movement. However, the occurrence of ephemeral surface flow is also closely related to the spring groundwater rising up to the soil surface at Lac Laflamme. When groundwater is high, a turbulent pipe flow occurs at the interface of the mineral and organic layers (Roberge & Plamondon, 1987). A temporary lowering of the water table usually coincides with the disappearance of this surface runoff. This close relation between groundwater level and stream network expansion is a clear illustration of the variable source area concept for streamflow generation. Even if it was known that ground frost (Freeze, 1972) with the succession of melting and freezing periods could produce conditions favouring surface flow, we considered that this type of flow was limited in space and time on the Lac Laflamme basin. Thus, the VSAS2 runoff model was selected.

THE VSAS2 RUNOFF SIMULATOR

The hydrological simulator VSAS2 (Bernier, 1985) is based on the physical processes governing water movement in a basin. The input data necessary to use VSAS2 are surficial topography, geometry of deposit, soil hydrodynamic properties and water input to the soil surface. There are no adjustment parameters included in VSAS2 since it is totally based on basin and soil physical properties. The model predicts water outflow and soil water content, layer by layer for all sub-basins and a global stormflow hydrograph for the entire basin.

In the simulation, water input to the soil surface was obtained from the SNOW-17 model, calibrated with a 20 m^2 lysimeter. Soil liquid-water content was measured with the time domain reflectometry technique (Stein & Kane, 1983). Groundwater level was measured along three transects perpendicular to the lake shore, in sub-basins C, D and F. Nitrogen bubble systems were used to measure yield at an H-flume located at the lake discharge, and to monitor lake water level.

RESULTS AND DISCUSSION

The actual streamflow (Q) pattern for average melt days (streamflow around 5 mm) has been well predicted (Fig.2). The simulation of lake water level and soil water content (SWC) also indicates that the processes involved in water routing through the basin were generally well reproduced by VSAS2 for these average events. However, in all cases low flows following the onset of melt have been overestimated, possibly due to errors in the evaluation of the water storage capacity (soil depth and initial water content) and hydraulic conductivity of the lower soil layer. This type of error is a major limitation to the simulation of variable source area response.

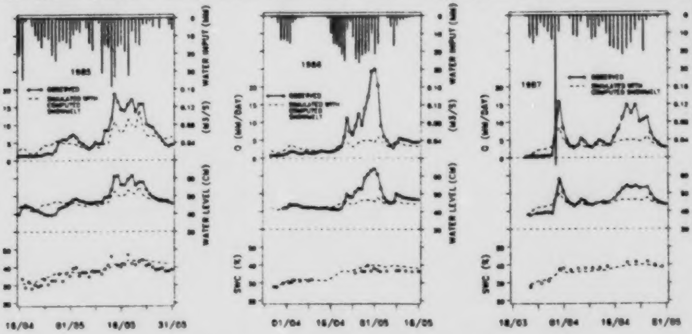

FIG.2 Actual and predicted lake water level, soil water content (SWC) and lake discharge (Q).

VSAS2 failed to generate the first peak flows (Fig.2). All high flows occurring during the last two to three weeks of each season were strongly underestimated. In order to assess the effect of inadequate quantification of soil hydrodynamic properties on the prediction error, simulations were performed with values of soil porosity and saturated conductivity varying within their standard deviation. No significant improvement in the overall performance of the simulator was obtained. Even with extreme values of porosity and conductivity, the underestimation of stormflow indicates that surface runoff was produced by a larger area within the basin than the one simulated by VSAS2. Large segments and increments were used for Lac Laflamme basin and micro-relief of the site may have caused localized exfiltration zones long before the occurrence of surface saturation over the complete width of a VSAS2-defined segment.

The expansion of contributing zones was also related to special soil conditions encountered during snowmelt, when groundwater is high or the surface horizon frozen. These intermittent conditions were probably crucial in the generation of melt peak flows, but remained impossible to reproduce through computer simulation. Unfortunately, there is no mechanism in VSAS2 to simulate failure to infiltrate due to soil freezing. THis phenomenon, like pipe flow promotes runoff. Both may represent a major source of incoming water to the lake during stormflows.

The problem is that physical properties of the soil (porosity, conductivity) vary over space and time. The prediction of these variations and their inclusion in the simulator would be a solution. However, the development of a physical representation of these phenomena for the balsam fir forest would be the object of an extended study which exceeds the limits of the present work. The next part of this paper will aim to investigate the dynamic of infiltration and to define the way of future research efforts.

The snow cover extent determines the degree of exposure of wetted soil to nocturnal freezing conditions. For every season, it was possible to relate the snow cover areal extent to the pattern of streamflow hydrograph (Fig.3). In all cases, the last rising limb of the hydrograph corresponded to significant decreases in the snowpack extent. The fraction of bare ground was therefore used as an index to the decrease of infiltration capacity on the basin. To take into account failure to infiltrate in the simulation, values of snow cover extent were taken from SNOW-17 results and included in VSAS2 inputs. THe proportion of bare areas generated by SNOW-17 was treated as representative of impervious surfaces.

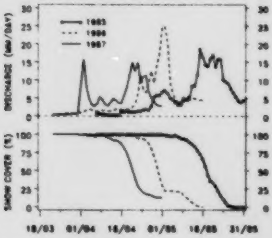

FIG.3 Relation between areal extent of the snow cover and discharge hydrograph.

The inclusion of a "snow cover areal extent factor" in VSAS2 strongly improved simulation results (Fig.4). Most of the peak flows have been well predicted. This indicates that when the snow cover is discontinuous, the combination of water exfiltration, pipe flow and ground frost can produce important surface flow. This is also an indication that the snow cover extent can be used as an index for infiltration during snowmelt at Lac Laflamme.

As a whole, VSAS2 proved to be a useful tool to investigate snowmelt pathways on the Lac Laflamme basin. However, the duration of the simulated periods (800 to 1200 hours) and the iteration process that was included have made the simulator to be a high CPU time requiring program (1 to 10 s of CPU time per simulated hour, per segment). For future applications, it should be modified to avoid extra computation for elements that do not present convergence problems. At this point, it is also foreseen that further efforts on snowmelt runoff modelling at this site must be mainly oriented on the study of

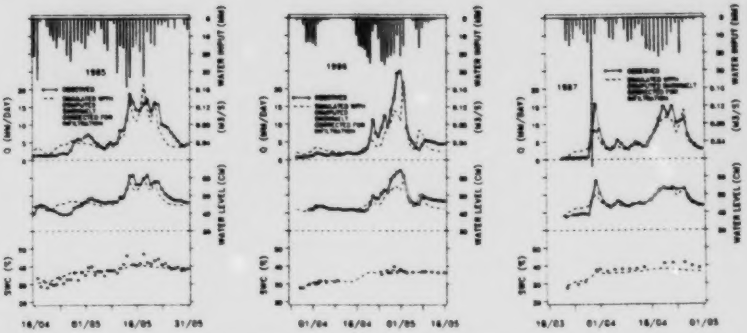

FIG.4 Actual and predicted lake water level, soil water content (SMC) and discharge hydrograph (Q) using an infiltration factor.

the dynamics of infiltration process into frozen ground. It should focus on the interactions between fluctuations of air temperature, antecedent soil moisture content, antecedent snowmelt and areal extent of the snow cover. A method has to be found to predict the formation, extent and permeability of frozen soil in the late spring period.

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Snowmelt runoff on the lac Laflamme watershed

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ABSTRACT The contribution of the different runoff flowpaths during snowmelt is of major importance for assessing the impact of environmental factors on water quality. The purpose of this paper is to evaluate the contribution of subsurface and surface runoff during snowmelt in a balsam fir forest located in the laurentidian upland watershed of Lac Laflamme (47°N, 71°W) using the hydrological model HYFOR. Watershed runoff was simulated with the HYFOR model during the snowmelt periods of 1985, 1986 and 1987. Lysimeter and calculated snowmelt runoff at the base of the snowpack were used as inputs to the model. The calculated values were obtained from a temperature index snow cover model. The initial simulations showed a poor ability to predict runoff. The soil porosity and hydraulic conductivity were modified to account for the ground frost effect because some of the soil properties evaluated in the laboratory or measured during non-frost conditions are different than those of frozen soils. Simulations were substantially improved by reducing soil porosities by 31% and hydraulic conductivities by 53% of their values measured under frost free conditions. Surface flow volume (including pipe throughflow) computed with the calibrated model varied between 32% and 47% of the total volume for the snowmelt period. Because of the significant modifications of soil parameters necessary to obtain reasonable model performance, it is concluded that better field observations of ground frost effects on soil hydrologic properties are needed to improve snowmelt runoff simulations.

RÉSUMÉ L'objet de cette étude était d'évaluer, au moyen d'un modèle hydrologique (HYFOR), la contribution de l'écoulement de surface et souterrain durant la période de fonte nivale dans un bassin de tête (Lac Laflamme) situé dans une sapinière laurentidienne du Québec (47°N, 71°W). Le modèle HYFOR a été utilisé durant les périodes de fonte 1985, 1986 et 1987. L'écoulement observé au moyen d'un lysimètre et les valeurs calculées au moyen d'un modèle à indice de température furent utilisées comme entrées au modèle. Les premiers résultats de simulations furent insatisfaisants. Puisque les propriétés du sol évaluées en laboratoire ou mesurées durant l'été sont différentes dans les sols soumis au gel, la porosité et la conductivité hydraulique du sol furent modifiées pour tenir compte du gel partiel du sol. Les résultats de simulation furent améliorés substantiellement lorsque la porosité et la conductivité hydraulique du sol étaient réduites respectivement de 31% et de 53% de leurs valeurs mesurées en laboratoire ou en condition sans gel. Le volume d'écoulement rapide de surface (incluant l'écoulement en conduits) calculé au moyen du modèle calibré pour la période de fonte de la neige variait de 32 à 47% du volume total. En raison des ajustements majeurs requis aux paramètres du sol pour obtenir des performances acceptables du modèle, il est conclu que de meilleures observations in situ des effets du gel sur les propriétés hydrologiques du sol demeurent nécessaires pour l'amélioration de la simulation des écoulements en période de fonte.

INTRODUCTION

For regions where the main hydrological input originates from snowmelt, testing of physically-based hydrological models is needed as a prediction tool and as a way to investigate the peculiar flow processes occurring in the presence of partial ground frost. The objective of this study was to apply a deterministic hydrological model to assess the runoff contribution of subsurface and surface flow from the different parts of a small upland watershed located in the coniferous forest north of Quebec City. The HYFOR model (Fox, 1976) was selected to satisfy this objective and to evaluate, through the calibration procedure, the possible effects of ground frost.

Roberge & Plamondon (1987) studied flow pathways on a part of the Lac Laflamme watershed using a trench collecting saturated-unsaturated downslope water flows in different soil layers. They determined that lateral unsaturated flow was negligible and that subsurface flow through the till layer was the major contributor to runoff. Furthermore, some pipe throughflow occurred at the mineral-organic interface when the water table reached the top of the mineral soil. The observations of these authors remain to be verified on a watershed scale where both the depth of the till deposit as well as snowmelt inputs are highly variable. Whether or not these findings apply to an entire watershed can be verified using a hydrological model.

SITE

The upland first order watershed of Lac Laflamme (47°N, 71°W), located 80 km north of Quebec City, covers 68 ha of which 6 ha are occupied by the lake. The watershed elevations range from 777 m to 864 m and slopes vary from 0 to 30% (see Fig.1 in Prévost et *al.*, this proceedings). Average annual precipitation is 1400 mm of which one third falls as snow. The forest consists of 80% 50 year old balsam fir (*Abies balsamea* (L) Mill.), averaging 5000 stems per hectare, 10% white spruce (*Picea glauca* (Moench) Voss.) and 10% white birch (*Betula papyrifera* Marsh.). The mineral soil is covered by an organic layer about 5 to 10 cm thick. The impervious charnockitic gneiss bedrock is overlaid by a sandy till rich in cobbles and boulders.

METHODS

Application of the model

To apply the HYFOR model and to correct snow cover outflow for spatial variability, the watershed was subdivided into 9 segments. The model was first run for the snowmelt periods of 1985, 1986 and 1987 with observed soil parameters and water inputs provided by the SNOW-17 model previously calibrated with a snow lysimeter located on the site. The main adjustment done to improve simulated flows with HYFOR was to modify soil parameters. This was done through a sensitivity analysis performed using the lysimeter data of 1985 as input. The model was run with the adjusted soil parameters using the SNOW-17 computations of snow cover outflow as input for the three seasons. The initial soil moisture was estimated on 21 stations at 10, 20, 40 and 80 cm from the soil surface. Further details on the snow and soil water analysis can be obtained from Barry (1988) and Prévost (1988).

Most of the geomorphological parameters were measured on the site or were obtained from existing maps. Till deposit depths measured at 24 points on the basin were used to build fourth degree regressions for assessing bedrock configuration between the measured points. Hydrologic properties of the deposit (saturated hydraulic conductivity (KS) and porosity) were measured with 820 cm^3 soil samples collected at 10, 20 and 40 cm on different sites of the watershed. KS was estimated in laboratory with a steady state permeameter. Measurements of KS for deep layers (1 to 3 m) was done in deep wells using in situ methods (Robitaille & Wilhemy, 1981).

The principal verification of the model was done with the discharge at the lake outlet monitored with a Parshall flume. Measurements of soil moisture at station C1 were also used to verify the soil moisture predicted by the model. Groundwater levels were used as verification data for the saturation of each soil layer. They were monitored with 10 observation wells 1 to 3 m deep located on the instrumented plot (C1).

The criteria for assessing the performance of the model were the mean values of the absolute departures, the Pearson correlation coefficient, and the Nash & Sutcliffe (1971) efficiency coefficient (N).

RESULTS AND DISCUSSION

Simulation results

The first simulations were done with parameters measured in summer either in the laboratory or in the field. The model, without calibration, provided poor simulation results (Fig.1). Values for the efficiency coefficient were low (0.59, 0.22, and -0.06 for 1985, 1986 and 1987 respectively). Most of the observed peaks were not simulated at all or predicted only very weakly. Since 1) cold water's high viscosity reduces its velocity and 2) frozen soils often been found to have much lower storage and infiltration capacities, modifica-

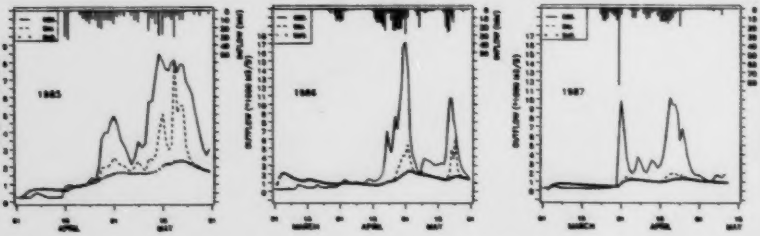

FIG.1 Daily discharge observed at the lake outlet (OBS), simulated by the HYFOR model without calibration (SIM), and the computed subsurface flow contribution (SUB).

tions of the soil porosity and hydraulic conductivity were carried out to improve the model performance.

Assessing soil water temperature and ground frost effects

The change in the fluid viscosity is most responsible for the reduction in the saturated hydraulic conductivity (Klock, 1972). The hydraulic conductivity tests for the first 60 cm were conducted in the laboratory with water at about 16°C and a viscosity of 1.109 centipoise. Assuming that snowmelt water remains at 0°C while infiltrating the first 60 cm, the viscosity of water should reach 1.787 centipoise. This results in a reduction of the saturated hydraulic conductivity of 38% of the laboratory value. Thus, the saturated hydraulic conductivity of the first 60 cm was reduced to 398.2 cm d^{-1}.

Among the three types of frost that may affect soil hydrologic properties in northeast North America (concrete, stalactic and granular frost), the latter is more likely to be found in woodland soils with high organic content (Trimble *et al.*, 1958). Although spotty concrete frosts may sometimes occur in forest soils, large unfrozen holes and patches still allow water to enter the soil. Kane & Stein (1983) found that ground frost decreased soil permeability by a factor 10-100 (depending on the soil ice-content) for a Fairbanks silt loam.

Soil effective porosity can also be modified for the 0 to 60 cm layers where ground frost is likely to occur. A crude estimate of the reduction of effective soil porosity by frost can be obtained from the observations of Anderson & Morgenstern (1973) on West Lebanon Gravel and Fairbanks silts. They observed reductions of 40% of the unfrozen water content when soil temperature decreased from 0°C to -0.8°C for a saturated sample. At station C1, the soil temperature for the 10 cm depth was between -0.4 and -1.2°C and between -0.1 and -0.6°C for 20, 30, 40, and 60 cm depths (Barry, 1988).

The unfrozen water content did not reach actual saturation porosity at 10, 20 and 40 cm before May 13 in 1985 and later in 1986 and 1987. The maximum unfrozen water content occurring before May 13 in 1985 was 0.30, 0.41 and 0.42 $cm^3\ cm^{-3}$ at 10, 20 and 40 cm rather than 0.60 (occurring later in the season) which is the actual saturation porosity for these soil layers. These low unfrozen water contents were maintained during almost 3 weeks while the water table was very close to the soil surface. Thus it can be assumed that a soil porosity reduction between 25 and 50% for the 60 cm top layer would be a reasonable approximation during the time when soil temperatures varied between -0.2 and -1.2°C.

The model was adjusted by testing it with several different values of effective porosity (POR) and saturated hydraulic conductivity (KS). The model showed a high sensitivity to changes in the effective porosity for peak flow, and no noticeable sensitivity during presnowmelt baseflow. Reductions of 25% in effective soil porosity did not result in an appropriate change in volume and a pronounced lag for the appearance of the first major peak occurred. On the other hand, reductions of 50% resulted in the computation of a very large surface flow contribution and a very rapid response to the first melt inflows. The best adjustment was obtained with a reduction of 31% of the measured value of porosity.

Saturated hydraulic conductivity (KS) was adjusted using a similar procedure. Values of KS were selected according to observations reported in the literature (e.g. Trimble *et al.* 1958). KS values measured at 16 °C (643 cm d^{-1}) were first increased by 56% (1000 cm d^{-1}) to take into account of the possible KS augmentation observed by Trimble et al.(1958). Next, the original KS values were adjusted for increases in viscosity (398.2 cm d^{-1}) and were further reduced by either 25% or 50% to take account for the effects of frost. As expected, sensitivity of the model to the KS parameter was very high. The best adjustment was obtained with a KS value of 300 cm d^{-1} which represents a reduction of 25% of the viscosity corrected KS value.

Model performance with adjusted parameters (calibrated model)

The model calibrated with the 1985 lysimeter data provided better results for the three seasons than the model using the measured soil porosity and hydraulic conductivity (Fig.2). The average efficiency coefficient for the three seasons of simulation was improved greatly by using lower values of soil porosity and hydraulic conductivity (0.27 to 0.69). This improvement was quite marked for 1987 when N passed from -0.06 to 0.64 but was also significant for the 1985 and 1986 seasons. Although modifications to soil parameters resulted in significant improvement of runoff peak simulation, some of the large and small peaks remained underestimated while presnowmelt baseflows were overestimated (Fig.2).

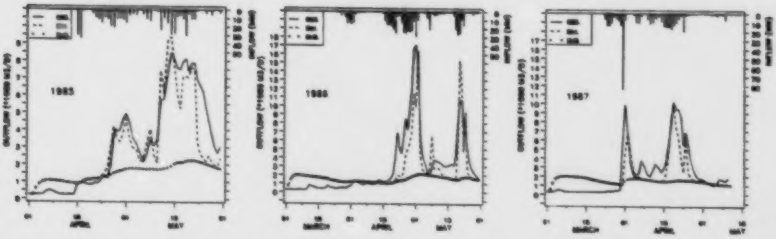

FIG.2 Daily discharge observed at the lake outlet (OBS), simulated by the HYFOR model after calibration (SIM), and computed as subsurface flow contribution (SUB).

The total outflow volume simulated by the calibrated model were relatively closed to the observed volumes for 1985 but were underestimated for 1986 and 1987 (Table 1). Subsurface flow was the major contributor of the predicted outflow, representing 53%, 59%, and 68% of the simulated total outflow for 1985, 1986 and 1987, respectively. While subsurface flow yielded water volumes seldom exceeding 3000 m^3 d^{-1} (about 4 mm d^{-1}), an important part of the peak flows was generally simulated as surface flow components (including overland and pipe throughflow at the mineral-organic interface). During the major peak flows occurring at the end of each season, surface components sometimes contributed close to 60% of the simulated daily outflow of the whole basin.

A comparison of the predicted surface flow contribution by the HYFOR model (adjusted) with estimations of pipe throughflow by Roberge & Plamondon (1987) for some events of 1985 reveals important departures. Computations for a part of the slope feeding an intermittent stream in the elevation zone 1 of segment C (for which Roberge and Plamondon performed their calculations) and predictions for the whole watershed did not agree. They estimated a pipe throughflow contribution generally lower than 20% of the measured yield of the stream. This contribution was lower than that computed by the calibrated HYFOR model. However, they estimated that over 75% of the flow was pipe

TABLE 2 Comparison between observed outflow and that predicted by the calibrated model.

Period	Total Volume (dam³)		Maximum Yield (dam³ d⁻¹)		Average Departure (dam³ d⁻¹)	Pearson Correlation Coefficient	Predicted Surface Flow	
	OBS	PRED	OBS	PRED			Volume (dam³)	%
01/04-01/06/85	198.5	199.6	8.47	9.85	1.07	0.83	94.0	47
01/03-01/06/86	278.7	246.7	17.11	16.43	1.45	0.84	101.8	41
01/03-01/06/87	166.2	158.1	10.19	9.69	1.24	0.81	51.0	32

throughflow for a major peak at the end of the season, a much higher value than that computed by HYFOR. Simulations by HYFOR model produced high surface flow contributions for the zones with thin soil deposits and computed much lower surface flow contributions for the lower parts of the watershed with thicker soil deposits (e.g. Segment C lower zone 1).

The calibrated HYFOR model yielded reasonable results of water yield at the lake outlet, surface runoff, subsurface flow, soil water and groundwater level when the porosity and hydraulic conductivity were adjusted for modifications that may occur during snowmelt season. The model indicated that surface flow, which includes both surface pipe throughflow and overland flow, may contribute up to 80% of the daily runoff during snowmelt for the upper elevation zones. The calibration and testing of the model was useful in identifying needs for more detailed research. More field work on the dynamics of soil porosity, hydraulic conductivity, and infiltration during springtime would substantially improve the simulation of soil water movement within boreal soils. This would undoubtedly help gain further insights into the relative contributions of flow generation components during snowmelt in northern balsam fir forests.

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Atrazine decay study in the Nissouri Creek Watershed

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ABSTRACT As part of a three-year study to "Model the Environmental Fate and Transport of the Herbicide Atrazine in an Agricultural Watershed", the Ontario Ministry of Environment carried out on-farm studies to determine atrazine decay rates from soils. Field surveys during 1985 and 1986 on corn fields located within the major representative soil types in the Nissouri Creek agricultural watershed provided suitable experimental data to support a model calibration. Atrazine levels in the soil declined exponentially following the equation: $\mathrm{Log}\ C = a + kT$, where, C is the herbicide residue in soil, and T is time in days elapsed since application. The half-life dissipations of atrazine in the surface profile were 46 days, following post-emergent application on the Embro silt loam, and 94 days, following pre-emergent application on the Guelph loam. Atrazine concentration at lower depths were minor due to low level percolation from upper profile. The residue levels at depth were in the order of 10% of surface values at 60 days after application.

RÉSUMÉ Le Ministère ontarien de l'environnement a étudié, sur des terres agricoles, les taux de décomposition de l'atrazine dans le sol au cours d'une étude de trois ans sur "la modélisation du sort environmental et du transport de l'herbicide atrazine dans un bassin agricole". Les données pour le calage du modèle allaient provenir de relevés de terrain effectués en 1985 et 1986 dans des champs de maïs localisés sur les principaux types de sols du bassin agricole de Nissouri Creek. Les niveaux d'atrazine dans le sol ont décru de façon exponentielle suivant la relation: $\mathrm{Log}\ C = a + kT$, où C est le résidu d'herbicide dans le sol, et T est le temps en jours écoulé depuis l'application. La demi-vie de dispersion de l'atrazine dans les horizons de surface était de 46 jours après une application post-émergence sur le loam limoneux Embro, et de 94 jours après une application pré-émergence sur le loam de type Guelph. Les concentrations d'atrazine dans les horizons inférieurs étaient faibles à cause du peu de percolation en provenance des horizons supérieurs. Les niveaux résiduels en profondeur n'atteignaient que 10% des niveaux résiduels en surface 60 jours après l'application.

LOCATION

The fate of agricultural chemicals and the potential risk to the environment have been of major concern to the Ontario Ministry of the Environment. In 1985, a field study was established to determine the decay rate of herbicides as part of a watershed modelling management study (Beak Consultant Ltd, 1987; See also Logan et al, this proceedings).

Because of extensive use in Ontario (McGee, 1984) atrazine was selected as the test chemical. Atrazine is a member of the S-triazine herbicide compound, known chemically as 2-chloro-4-ethylaminc-6-isopropylamino-S-triazine. The S-triazine compound has a direct relationship between water solubility and absorbability in soil. Soil organic matter has an adsorbing characteristic with S-triazine; in addition, atrazine has shown greater absorptive characteristics under humic acid condition than under neutral acid condition (Khan, 1980). Early works have shown runoff losses of atrazine from soil under simulated rainfall conditions (Khan, 1980). Later studies demonstrated actual pesticide runoff from watersheds (Haith, 1980).

Atrazine is also lost from soil by degradation through chemical hydrolysis. The kinetics of the hydrolysis indicated that the half-life value of atrazine increases with elevated pH level in aqueous fulvic acid solution (Kahn, 1980). Further studies have shown the extent to which atrazine residues may persist in soil after repeated application (Kahn, 1980). Atrazine level may be reduced by a change to its metabolite, deethylated atrazine, which may persist in soil for twelve months after atrazine application (Kahn, 1980). Frank & Sirons (1985) have observed atrazine decay rates in various Ontario soil types indicating half-life dissipation of 3 to 3.6 months. The objective of this survey field study was to determine the environmental decay rate of atrazine in soil types of the Nissouri Creek watershed.

STUDY AREA

The Nissouri Creek watershed is an agricultural area of 30 km^2 in southern Ontario. The major soil types are Guelph loam and Embro silt loam which makes up 81% of the drainage area. The drainage area is serviced by a tile drainage system. The crop production is a mixture of grain crop, 50% of which is in corn. Atrazine is the primary herbicide applied to control broad-leaf weeds in the corn fields.

SAMPLING METHODS

Decay studies were carried out in 1985 and 1986. A test plot of area 50 m by 10 m was established in a corn field on the Embro silt loam which contains neutral pH conditions. A post-emergent application of Aatrex Nine-o (90% atrazine) was applied at a rate 2.2 kg ha^{-1} on May 30, 1985. Following application, soil samples were taken at soil profile depths of 0-2 cm, 12-18 cm and 30-35 cm at varying sampling intervals, ranging from 1 to 15 days. Soil samples taken at several locations were composited to form triplicate sets which were refrigerated and submitted for laboratory analysis.

In 1986 a similar plot size was established on the Guelph loam, which had good drainage and neutral pH conditions. A pre-emergent application of Chipman atrazine flowable liquid was applied at a rate of 1.2 kg ha^{-1} on May 12, 1986. Triplicate soil samples were collected at depth 0-5 cm, 12-18 cm and 30-35 cm at varying sampling frequency. The samples were composited, refrigerated and submitted for laboratory analysis.

LABORATORY ANALYSIS

Qualitative and quantitative analyses of the atrazine soil samples, using the Gas-liquid Chromatography (GLC), were carried out by the Ontario Ministry of Agriculture and Food Pesticides Residue Laboratory. The Frank & Sirons (1985) extraction approach was employed to remove the atrazine and deethylatrazine for analysis.

RESULTS AND DISCUSSION

The atrazine decay was examined by the first-order equation:

$$dC/dt = kC \qquad (1)$$

where C is the atrazine residue concentration at time, t; and k is the observed rate constant (t^{-1}).

The results of Frank & Sirons (1985) demonstrated the decay curve:

$$\log C = a + kT \qquad (2)$$

where T is the elapsed time. The disappearance of the compound may be approximated by the half-life $t_{1/2} = (.301T)/(\log C)$.

The exponential plots of atrazine decay for the surface samples indicated a half-life of 46 days for the post-emergent application and 94 days for the pre-emergent application. The decay rates of atrazine were comparable to the dissipation values of Frank & Sirons (1985). It should be noted that the pre-emergent application involved the mixing of spray applied atrazine into the soil shortly after spraying. The reduction of the exposure of atrazine to sun, wind, and higher temperature; and by mixing which increases the area of adsorption of atrazine to the soil particles, affect the degree of decay. The atrazine levels at depth 30-35 cm, showed no meaningful decay, only background level variations indicating low percolation of soluble atrazine. Similarly, no appreciable decays were observed at profile depth 15-18 cm, although evidence of atrazine was observed at that depth.

CONCLUSION

Field decay studies for the herbicide, atrazine, have been carried out to support a watershed modelling study to predict the environmental fate and transport of herbicides in Ontario soils. Varying decay rates were observed in different soil types, indicating atrazine half-life of 46 days and 94 days for the post and pre-emergent applications, respectively. The sub-surface samples showed no meaningful decays only background level variations of atrazine with instances of low level percolation from the surface.

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The speedvale experimental watershed

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ABSTRACT The Speedvale Experimental Basin was established in 1965 as an International Hydrological Decade project for the purpose of studying impacts of urbanization on hydrologic response. A relatively extensive hydrologic database regarding precipitation, streamflow, soil moisture, and groundwater was assembled for the preurbanization period from 1966 to 1974 and for the period of ongoing development from 1975 to 1982. The study area was used for mixed agricultural purposes prior to 1974. During 1975 and 1976, 155 ha of the basin were serviced for development for light industrial and commercial usage, dramatically altering the configuration of the drainage system. With the changes in land use in the basin have come changes in both volumetric and time distribution aspects of hydrologic response. Changes in the response include (i) an increase in the mean annual runoff coefficient by a factor of 1.5, (ii) an increase in the average annual maximum instantaneous discharge by a factor of almost 3.0, (iii) a change in the time of the annual peak flow, (iv) a change in the seasonal pattern of monthly runoff coefficients, (v) a 3-fold reduction in unit hydrograph lag time, and (vi) a 3.5-fold increase in unit hydrograph peak discharge.

RÉSUMÉ Le bassin expérimental Speedvale a été etabli en 1965 en tant que projet hydrologique international décennal, dans le but d'étudier les impacts de l'urbanisation sur la réponse hydrologique. Une base de données hydrologiques relativement considérable, concernant les précipitations, l'ecoulement du cours d'eau, l'humidité de sol et l'eau souterraine, a été assemblée à la fois pour la période de pré-urbanisation de 1966 à 1974 et la période de développement progressif de 1975 à 1982. La zone d' étude était utilisée à des fins agricoles mixtes préalablement à 1974. Au cours de 1975 et 1976, 155 ha du bassin ont été équipés d'utilités publics pour le développement de secteurs d'industries légères et commerciaux, modifiant dramatiquement la configuration du système de drainage. Les modifications de terrain faites dans le bassin ont été accompagnées de changement à la fois dans les aspects de la distribution temporelle et volumétrique de la réponse hydrologique. Les changements inclus dans la réponse sont (i) une augmentation du coefficient de ruissellement annuel moyen par un facteur de 1.5, (ii) une augmentation du débit instantané maximum annuel moyen par un facteur de presque 3.0, (ii) une modification du temps d'occurrence du débit de pointe annuel (iv) une modification du modèle saisonnier des coefficients de ruissellement mensuels, (v) une réduction de 3 fois dans le décalage dans le temps de l'hydrographe unitaire et (vi) une augmentation de 3.5 fois du débit de pointe de l'hydrographe unitaire.

BACKGROUND

The Speedvale Experimental Basin is a small watershed of 210 ha situated at the northwest corner of the City of Guelph, Ontario. The basin is a tributary area of the Speed River Watershed, forming part of the Lake Erie drainage basin, and hence part of the Great Lakes drainage system. The regional climate is subhumid continental with moderate winters and warm summers, the mean annual precipitation of 840 mm being uniformly distributed throughout the year. The mean temperature for February, the coldest month, is -6.3°C, and for July, the warmest month, 20.2°C.

The primary land use within the watershed prior to 1974 was of an agricultural nature. At that time, the watershed was 199 ha in area. The drainage system was comprised of open ditching in the lower half of the watershed with a well-defined mainstream channel extending from the outlet to a point 1700m upstream. Upstream, there was a large, nearly level area where surface water ponded during spring snowmelt and large summer runoff events.

During 1975 and 1976 an extensive servicing program was undertaken by the City of Guelph in preparation of the watershed area within the city limits for industrial development. The work consisted of widening the major arterial roadways and constructing new interior streets, installing a sanitary sewer system, installing a water distribution system, rough grading of industrial lots, and installing drainage system of open channels and a large-diameter storm sewer. The extensive land grading resulted in a change in the watershed boundary, with a net increase of 11 ha for a present total area of 210 ha.

By 1982 approximately 50% of the area within the city limits had been occupied, or about 45% of the watershed area, with the majority of the development occurring immediately after servicing of the area. The remaining area located within the city limits had been rough graded with the topsoil stripped and stockpiled, and the land supported a sparse weed and grass cover. The area outside the city limits remained in agricultural use.

No changes to the drainage pattern of the extreme upstream portion of the watershed, outside of the city limits, have been made. There is no ditching system draining this area; runoff occurs by overland flow and is intercepted by the rear-lot ditch on the north side of Malcolm Road. A portion of the area is tile drained and the outlet for the subsurface drainage system is to the rear-lot ditch.

RESEARCH BASIN DATA

Data collection for the Speedvale Experimental Basin was initiated in 1965 in conjunction with an International Hydrologic Decade research project. Data collection has included precipitation, streamflow, soil moisture, and groundwater measurements and recordings.

The streamflow stage from the Speedvale Experimental Basin was measured (station No. 02GA032) by the Water Survey of Canada from 1965 to 1982. During the period from 1965 to early 1975, stage measurements were made by means of a continuous recording gauge located 50 m downstream of Speedvale Avenue. Flow was controlled by use of a 3-ft H-type flume installed on a concrete approach constructed in the channel. Continuous water stage measurements were discontinued on March 11, 1975, and the flume removed when construction of the 3.0 m diameter storm sewer was taking place. On October 1, 1976, continuous recording measurements were again resumed. The gauging station, equipped with an automatic stage recorder, was relocated 10m downstream of the outlet for the 3.0 m diameter storm sewer, and a sheet steel pile weir was used in the channel bottom for a control. Digitized water level information is available for the period from January 1, 1970, through December 31, 1982, from the regional office of the Water Survey of Canada, Guelph, with the exception of the periods in 1975 and 1976 when the station was removed.

Precipitation inputs to the watershed were recorded by the Atmospheric Environment Service (A.E.S.) from 1966 to 1982. Rainfall measurements were made with a Fischer-Porter recording rain gauge, located at a site in the northern part of the basin. This gauge provided 15-min amounts of rainfall with an incremental amount of 2.5 mm. A Canadian Meteorological Standard rain gauge and a Nipher Shielded snow gauge were also located at the site with the Fischer-Porter gauge, giving 1-hour precipitation amounts, and were maintained until 1977 and a network of eight nonrecording rain gauges was maintained until 1972 by the University of Guelph. Digitized information for the Fischer-Porter recording rain gage is available for the period from Atmospheric Environment Service.

RESULTS

Change in Annual Response

The mean annual discharge volume before development was 5.89 x 10^5 m^3, compared with 9.44 x 10^5 m^3 after development (a significant difference at the 0.05 level), while the mean annual precipitation before development was 865 mm, compared with 920 mm after development (not a significant difference at the 0.05 level) The mean of the annual runoff coefficients for the after-development period, 0.506, was 1.5 times that of the mean of the before-development period, 0.343. The after-development mean annual runoff coefficient was significantly greater than the before-development value, providing an indication that the annual volumetric response has changed with urbanization. The mean annual maximum instantaneous flow after development was 3.158 m^3 s^{-1}, a significant increase (by a factor of 2.9) over the mean of 1.082 m^3 s^{-1} before development. Review of the dates of the maximum instantaneous discharge each year indicated peak flows before development occurred in the months of March, April, and May. Prior to urbanization, the annual peak flow occurred consistently in the spring runoff period when snowmelt contributed to runoff. An exception to this pattern occurred in 1974 when the peak flow occurred in mid-May, coinciding with occurrence of an extremely large rainfall event that was the cause of major flooding in downstream areas. After development, the annual peak flows occurred throughout the year during the various seasons. Spring runoff from the basin was no longer the single major factor leading to the annual maximum flood after development; rather, storm rainfall usually determined the annual peak flow.

A frequency analysis of the annual maximum instantaneous discharge values indicated an increase in the magnitude of the flood peak for any selected return period,T,after development of the watershed. The ratio of the annual flood peak under after-development conditions decreased as the return period of the flood increased.

Monthly direct runoff coefficients, defined as the ratio of the calculated monthly direct runoff volume and recorded monthly precipitation, were determined for each month of the assumed snowmelt-free period of April-October for the period of available digitized streamflow record (1970-1982). Derivation of the direct runoff volumes for each month involved separating the baseflow component from the available record of hourly instantaneous discharge values on the basis of an assumed linear groundwater storage reservoir (Cook, 1984). The resultant hourly direct runoff values were then used to calculate the monthly direct runoff volumes, and hence the direct runoff coefficients.

For the period of June-October, the after-development mean monthly direct runoff coefficients are significantly greater at the 0.05 level of significance, by factors of 3.2 for June, 12.6 for July, 19.1 for August, and 38.1 for September. There has been no significant difference for the months of April, May, and October.

In order to examine the effect of urbanization on parameters of the runoff hydrograph such as time to peak, peak discharge, and hydrograph time base, unit hydrograph were derived for the identified storms before and after development. The 54 storm events suitable for unit hydrograph analysis were divided into two data sets: one comprised of 34 events after development.

The unit hydrograph features of time to peak, peak discharge, and hydrograph time base were examined for change with urbanization of the basin. The means of these unit hydrograph parameters for each developmental condition have been summarized in Table 1. The mean time to peak decreased by a factor of 3, the mean peak discharge increased by a factor of 1.5. In all instances the difference was significant at the 0.05 level of significance.

TABLE 1 Characteristics of 1 h unit hydrograph

	Before development			*After development*		
Characteristic	*Mean*	*No. of obs*	*std dev*	*Mean*	*No. of obs*	*std dev*
Time to peak (h)	*6.55*	*20*	*3.05*	*2.15*	*34*	*1.02*
Peak discharge (m^3 s^{-1})	*0.040*	*20*	*0.028*	*0.135*	*34*	*0.062*
Time base (h)	*28.3*	*20*	*8.4*	*17.8*	*34*	*6.3*

COMMENTS

The Speedvale Watershed has proven to be an experimental basin in accord with the definition provided for the International Hydrological Decade. It remains the only such urbanizing basin in central Canada for which a useful data set has been assembled and significant results have been published. More analyses could and perhaps should be conducted on the data, and certainly the results need to be more widely publicized in the stormwater management community.

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Slope position as a determinant of infiltration rates

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ABSTRACT Prediction and modelling of the transport of environmental contaminants such as nutrients, chemicals, and sediment depend on the modelling of runoff, which in turn is a function of infiltration rates. The Hortonian concept of infiltration as a uniform process throughout a drainage basin has given way to the recognition that the moisture conditions governing infiltration vary dramatically throughout a drainage basin. Using a finite element model, a typically configured hillslope of homogeneous material was analyzed with respect to the infiltration rates to be expected at different slope locations. It was found that, for a precipitation rate of 7.5 cm h^{-1}, 1.5 times the saturated hydraulic conductivity, the infiltration rates were very low, less than 10% of the storm precipitation, in a zone extending 12 m upslope from the outlet. This was due to the low storage available there. The infiltration increased from this low value to 100% of the storm precipitation inn the 26 m immediately upslope from this lowlying zone. The highland plateau only reached saturation after nearly 4 hours of precipitation at this rate. There was very little reduction in infiltration in this zone. The effect of different precipitation and soil conditions were studied; saturation and seepage zones developed in the lower reaches of the hillslope, depending on such factors as the type of soil, the topographic configuration of the hillslope, the amount of zone provided for efflux at the right vertical boundary, and soil layering. It is very apparent from the results that modelling infiltration without taking these factors into account will not do justice to the actual processes occurring.

RÉSUMÉ La prédiction et la modélisation du transport de contaminants tels que les éléments nutritifs, les produits chimiques et les sédiments dépendent de la modélisation de l'écoulement qui, lui-même, dépend des taux d'infiltration. Le concept hortonien de l'infiltration uniforme à la grandeur d'un bassin a fait place à la constatation que les conditions d'humidité qui régissent l'infiltration varient énormément à l'intérieur d'un bassin. Grâce à un modèle à éléments finis, les taux d'infiltration escomptés ont été calculés pour différents points d'un versant type constitué d'un matériel uniforme. Le taux de précipitation utilisé était de 7.5 cm h^{-1}, soit 1.5 fois la conductivité hydraulique saturée spécifiée. Les résultats montrent les faibles taux d'infiltration, moins de 10% de la précipitaton, dans les 12 m inférieurs de la pente, à cause du faible potentiel d'emmagasinement dans cette zone. Le taux d'infiltration passe à 100% de la précipitation dans les 26 m s'étendant au dessus de cette première zone de 12 m. Le plateau supérieur ne montre pas lui non plus de réduction marquée d'infiltration, et met 4 heures à atteindre le point de saturation au taux de précipitation spécifié. L'effet de différents taux de précipitation et de différentes conditions du sol a aussi été étudié. Dans ces essais, la formation de zones de saturation et d'exfiltration dépendait du type de sol, de la topographie, de l'importance accordée à la face verticale d'exfiltration, et de la configuration des couches de sol. Ces résultats démontrent clairement que la modélisation de l'infiltration sans l'inclusion de ces facteurs ne peut représenter les processus en cours.

INTRODUCTION

Continuing environmental overloading of sophisticated herbicides and pesticides, as well as nutrients, have caused deterioration of water quality. Soil erosion, too, has long been recognized as contributing to a deterioration of both water quality and the agricultural potential of our land. All these components are transported as pollutants by water, either as runoff or by percolation to the groundwater body. The fundamental process governing this transport is infiltration since it determines both runoff and percolation, which in turn determines soil erosion and transport of attached chemicals on the one hand and the movement of chemicals to groundwater on the other. A major focus in physical hydrology for the past decade or more has been on the non-uniformity in the infiltration rate over the drainage basin, as caused by varying moisture content conditions governed by elevation and topographical factors. Sklash & Wilson (1982) and Abdul & Gillham (1984) dealt with the development of saturated faces (infiltration less than or equal to the hydraulic conductivity (ks)) and seepage faces (exfiltration zones) in the near stream regions of a basin. These zones develop in response to rainfall rates much lower than ks, conditions under which limitations on infiltration would not be expected if nonuniformity was not taken into account. This paper, highlights this nonuniformity, discuss the reasons for its existence, and quantify it in terms of hillslope position. This will be done through finite element modelling of rainfall on an idealized hillslope.

MODEL AND HILLSLOPE

The model used is a commercially available software package, PC-SEEP, developed by GEO-SLOPE, Ltd. It is a two-dimensional finite element model using the Galerkin weighted residual scheme for solving Richard's equation. It can handle either steady state or transient flow conditions in either the saturated or unsaturated zones. It can model saturated and seepage faces along any boundary in a transient condition. It can also model layered soil conditions.

The hillslope profile was chosen so as to give as realistic a representation as possible of 3 different hydrologic zones: firstly, zone 1 near the stream where the soil surface is near the water table and where little storage is available for infiltration; secondly, zone 2 which slopes steeply up to the plateau; zone 3, which is much above the water table. This profile is shown in Fig.1.

Both homogeneous and layered profiles were analyzed; the conditions were as follows. For the homogeneous profile, the assumed soil material had the characteristics of sand with a ks of 5 mm h^{-1} reducing 3 orders of magnitude as the soil suction increased from 0 to 100 kPa; the moisture content reduced from .61 to .15 in the same suction range. Both functions had a somewhat steeper portion at lower suctions. For the layered profile, it was assumed that this same material occupied the top 30 cm of the profile and was underlain with a material that had an order of magnitude lower ks but a less sharp reduction in the hydraulic conductivity (k) in the unsaturated zone. Zero flux boundaries were assumed to hold along the left vertical face and the bottom. The right vertical face was assumed to be an interface with a reservoir at an elevation of 9 m for all but one of the runs; for that one, it

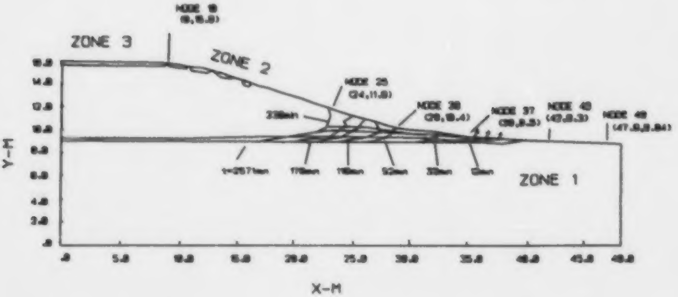

FIG.1 Water table locations at various times and velocity vectors. Homogeneous soil, time 230 minutes, precipitation 75 mm h^{-1} for 230 minutes.

was assumed to be a zero flux boundary except for the top 30 cm which was assumed to have a constant head of 9 m. Three precipitations were assumed: 2.5, 5.0, and 7.5 cm h^{-1}.

RESULTS

Only a sample of the results are shown; Fig.1 and Fig.2 show the results for the homogeneous material, a precipitation rate of 7.5 cm h^{-1}, and the entire right vertical boundary at a constant head of 9 m. The results of the other runs will be summarized. Fig.1 shows the variation in the position of the groundwater table with time during the precipitation, the direction of the velocity vectors at time=230 minutes, and the location an d coordinates of the nodes at which the infiltration versus time relationships shown in Fig.2 apply.

According to Fig.1, there was rapid growth of the saturated zone during the storm, with 15 m of near-stream slope length saturated during the first 12 minutes, extending to 25 m by t=230 minutes. The rate of growth decreased, as expected, where the surface slopes increased.

This entire zone was subject to limited infiltration; this would result in runoff. Fig.2 shows that the infiltration rate in this zone had decreased to near zero after 10 to 20 minutes of precipitation. The rate of drop of infiltration was somewhat lower 18 m up the slope at node 30, where the infiltration was half the precipitation after 30 minutes of precipitation, and tapered off to 10% of the precipitation at the end of the storm. The steeper part of the slope was not impacted as much as the lower parts. The infiltration 24 m up the slope was not impacted until almost two and one-half hours of precipitation had occurred, and was reduced to two-thirds the precipitation rate by the end of the storm.

Fig.1 and Fig.2 show that saturation occurred in the classical Hortonian manner on the flat zone 3 at the top of the profile. The ponding in zone 3 had its effect on the infiltration rate as shown in the drop in the infiltration of node 10. Saturation occurred along the flat section but no on the top part of zone 2 because the precipitation rate per unit length of surface was

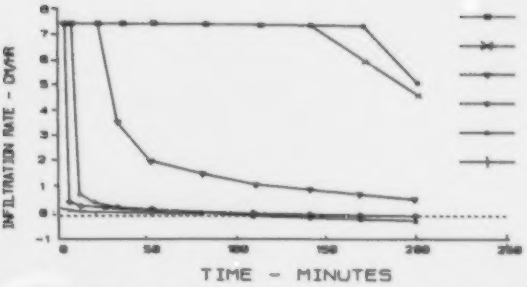

FIG.2 Infiltration variation along the hillslope for a homogeneous soil, precipitation 7.5 cm h^{-1}.

lower in zone 2 than in zone 1 due to the slope of the former.

There was a seepage zone approximately 3 m long centred at node 37. This is shown by the velocity vectors in Fig.1 and the negative infiltration shown for this node in Fig.2. It is noteworthy that the rate of exfiltration is a very small percentage of the precipitation rate or of the infiltration rate at other locations further upslope.

The actual amount of seepage was a much smaller proportion of the precipitation than that reported by Abdul & Gillham (1984) who found in their study of saturated and seepage zones that exfiltration could be of the same magnitude as the infiltration. The differences are due to three factors. The first is that, in our study but not in theirs, the entire downstream vertical face was assumed to be a flux boundary, discharging some of the flow from the water table mound which would have exfiltrated in their case. As evidence of this, when we reduced the downstream flux boundary to 30 cm from 9 m, the entire 12 m from node 36 to the stream become a seepage face. The second factor is that the slope of the water table and thus the head gradient is limited by the low slope of the ground surface in this region. The slope in their case was higher. Thirdly, in our case but not in theirs, there was a great deal of available storage to the left of the water table mound causing a significant amount of flow into this region as can be observed by the rising of the water table there. This was not due to infiltration from the surface above since it had not progressed more than 1.5 m below the surface by the time the water table started to rise.

It should be noted that the water table under zone 3 continued to rise after the end of the storm whereas the top of the water table mound started to flatten out and to drop below the ground surface closer and closer to the right vertical boundary. Forty hours after the end of the storm, the water table was at its maximum elevation under zone 3 and saturation still occurred over part of zone 1. By this time, the wetting front had progressed down 7 m so the rise in water table under zone 3 was due both to flow from the mound under zone 2 and from percolation from above.

The results for the lower precipitations, 5 cm h^{-1} and 2.5 cm h^{-1}, were similar to those for the 7.5 cm h^{-1} rate. Since neither of these precipitation rates exceeded ks, the surface soil in zone 3 was near, but not at, saturation. Thus the only saturated zones occurred on zones 1 and 2. It was somewhat surprising that the length of the saturated zone at the 5 cm h^{-1} precipitation rate was very nearly that at the higher rate. The length of the saturated zone was reduced considerably at the 2.5 cm h^{-1} precipitation rate. Generally, it can be concluded that, as expected, the size and strength of the seepage face decreased with a decrease in the precipitation rate but the way in which this varies could use further study.

Although the results are not shown here, layering also had considerable impact on the results. It prevented flow from the peak of the groundwater mound to the region under zone 3. This resulted in a greater rise of the water table up the slope in zone 2. Even though the precipitation was only 5 cm h^{-1}, the saturated zone extended to within 4 m from the top of the slope in zone 2. There was no development of a seepage zone in this case.

Storm infiltration as a percentage of precipitation was also determined for each of the 6 nodes. At a precipitation of 5 or 7.5 cm h^{-1}, from nodes 37 to 48 only about 5% or less of storm precipitation infiltrated. At node 30, it was 35% or less, and 31% for the layered case. At node 25 it was about 90% but 74% for the layered case. The percentages were all higher, at the lower precipitation rate of 2.5 cm h^{-1}.

On the basis of these results, it can be concluded that there exists an extensive zone inn the lowlands of a drainage basin which will experience very limited infiltration. It can be expected that those zones nearest the stream will yield relatively high runoffs, regardless of the precipitation rate. The runoff would be affected by the precipitation rate and the configuration of the hillslope, particularly the surface slopes, the flow zones available for efflux, and the soil layering. Seepage zones of variable size will also develop, depending on these factors. Prediction and modelling of runoff must take these non-uniformities in infiltration rate into account.

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Snowmelt contributions to spring runoff in acid stressed headwater streams on the Canadian shield

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ABSTRACT Spring runoff of three headwater streams in the 'Acid Precipitation in Ontario Study' (APIOS) area, differing greatly in their capacity to neutralize acidic deposition, was separated into pre-event (old) and event (new) water components using the stable isotope deuterium (D) as a conservative tracer. In all three catchments, new water comprised a substantial fraction of spring runoff with the highest daily contributions observed at peak flows (43-68%). New water remained an important component of streamflow during post-snowmelt baseflow (30-62%) indicating that mixing/displacement of groundwater with infiltrating meltwater had occurred in all three basins. The largest new water contributions to peakflow and post-melt baseflow were observed in the smallest headwater catchment. Stream pH was not directly related to new water contributions because (1) a considerable proportion of snowmelt water reached the stream via return flow with a pH close to that of old water and (2) a conifer swamp in one catchment acidified both old and new water. The acidification of such headwaters may largely be controlled by the ability of the system to buffer infiltrating meltwater with only short residence times in the soil and by the occurrence of wetlands in the lowlands which can act as an important acid source even during the highest flows of spring runoff.

RÉSUMÉ Les débits de fonte de trois ruisseaux, possédant des potentiels de neutralisation différents, et localisés dans la zone du projet "Acid Precipitation in Ontario Study (APIOS)" ont été séparés en leur eau pré-fonte (vieille eau) et eau de fonte (eau nouvelle) en utilisant l'isotope stable deutérium (D) comme traceur. Dans chacun des ruisseaux, la proportion d'eau nouvelle était élevée, avec des contributions maximales journalières durant les débits de pointe (43-68%). Dans les débits après-fonte, la proportion d'eau nouvelle est restée élevée (30-62%) indiquant un bon mélange/déplacement de l'eau souterraine par l'eau de fonte sur les trois bassins. Les plus fortes contributions d'eau nouvelle aux débits de fonte et d'après-fonte ont été observées sur le plus petit des trois bassins. Aucune relation n'a été observée entre le pH et le contribution de nouvelle eau parce que (1) une forte proportion de l'eau nouvelle a atteint le ruisseau par un cheminement souterrain avec un pH quasi égal a celui de la vieille eau, et (2) une tourbière boisée dans un bassin acidifiait à la fois l'eau nouvelle et la vieille eau. L'acidification de ces eaux de tête pourrait être déterminé en bonne partie par la capacité du système à tamponner l'acidité des eaux de fonte ayant un court temps de résidence dans le sol, et par la présence de

tourbières qui peuvent agir comme source d'acidité importante même durant les crues de fonte.

INTRODUCTION

Several calibrated watersheds in the Muskoka-Haliburton area in central Ontario have been monitored intensively since 1976 by the Ontario Ministry of Environment (O.M.E.) as part of the 'Acid Precipitation in Ontario Study' (APIOS) to study the effect of acid deposition on freshwater ecosystems on the Canadian Shield (Dillon *et al.*, 1978 ; Scheider *et al.*, 1979). The study area was chosen for this purpose since it receives relatively high rates of acid deposition and the buffering capacity of the soils and underlying bedrock is very limited (Lazerte & Dillon, 1984). Most of the streams in the APIOS study area are subject to pH depressions during spring runoff when large amounts of acidic meltwater are released from the accumulated snowpack (Jeffries *et al.*, 1979). However, the extent of the pH change varies considerably between streams. The different changes in stream pH may reflect the ability of the soil and groundwater to buffer this acidic input or result from different flowpaths of meltwater through the different catchments or both.

This study compares the contributions of snowmelt and rain (new water) to spring runoff in three headwater streams with different streamwater pHs. Using the isotopic technique of streamflow separation (Dincer *et al.*, 1970) we test the hypotheses that (1) different amounts of new water contributing to stream flow (via direct input onto saturated areas or indirectly via return flow) can explain the differences in pH depressions observed in the streams and (2) the size of the groundwater (old water) reservoirs in the three basins is inversely correlated with the degree of stream acidification.

BACKGROUND

The streams of two APIOS sub-basins, Harp-5 (A_w 195.3 ha) and Plastic-1 (A_w 23.3 ha), located less than 30 km apart, were compared in this study. A first-order stream (Plastic-108) draining a small upland valley (A_w 3.3 ha) within the latter sub-basin was sampled also. This small stream feeds into a centrally located conifer swamp before reaching the Plastic-1 outflow weir. The Plastic-1 watershed is dominated by very shallow (<1 m) coniferous forested till soils. The surficial deposits in Harp-5 range in depth from <1 m in the upland areas to 5-10 m in the central lowland portions of the basin supporting a mixed hardwood and coniferous forest.

Stream runoff was separated into new (melt/rain) and old water (soil/groundwater stored in the catchment prior to melt) using the stable isotope deuterium (^{2}H or D) as a conservative tracer. Prior to spring runoff the D in ground/soilwater was much greater than that of the meltwater. This difference was used to determine the contribution of old water to stream runoff on the basis of steady state mass balances (Dincer *et al.*, 1970):

$$Q_o = Q_s * \frac{(C_s - C_n)}{(C_o - C_n)} \tag{1}$$

where Q = discharge, C = concentration of the isotope, and the subscripts $_s$, $_o$, and $_n$ refer to the stream, old and new water components respectively. C_o and C_n were assumed to be represented by D of presnowmelt stream baseflow and the volume weighted mean D of snowmelt and rain input respectively obtained for each sub-basin.

RESULTS AND DISCUSSION

The temporal pattern of daily discharge and areal discharge measured during the 1987 spring runoff were very similar for all three streams. The temporal trends of D in stream and meltplots and the calculated hydrograph separation for Plastic-108 are shown in Fig.1 and are representative of the general pattern observed in the other two studied streams (not shown). New water comprised a substantial fraction of the total spring runoff from March 1 to April 30 in all three studied streams (Table 1). The highest new water fractions was observed in the smallest headwater stream (Plastic-108) and the smallest fraction was measured in the higher-order stream, Harp-5.

After all the snow had melted, new water remained an important component in all three streams throughout the post-melt recession to baseflow (Fig.2) indicating that considerable mixing/displacement of groundwater with infiltrating meltwater had occurred. The proportion of new water estimated from the streamflow separation during the recession provides an estimate of the amount of 'dilution' of the groundwater reservoir with new water. The dilution was much higher in Plastic-108 (62%) than in Harp-5 (30%) suggesting that the small upland basin had a much smaller groundwater reservoir than the larger Harp-5 catchment (Fig.2).

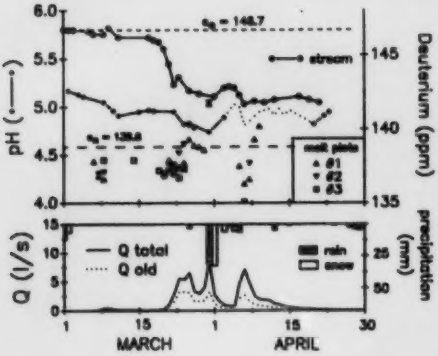

FIG.1 Temporal trends in stream pH (• ——•) and D (o —— o) for Plastic-108 during spring runoff 1987. Open symbols show D in composite samples from meltplots. C_p *and* C_E*, used for hydrograph separation, are indicated as dashed lines (top plotting). The mean daily runoff* Q_T *and the calculated* Q_p *are shown on the bottom plotting. The snowpack water equivalent prior to March 1 was approximately 125 mm.*

Stream pH was not directly related to new water contributions (Table 1). We believe that this occurred because a considerable proportion of the snowmelt water reached the stream as return flow, with a pH close to that of new water. This buffering mechanism was particularly effective during the initial phase of snowmelt when the most acidic meltwater was released and could infiltrate the very dry soils. However, in upland areas (e.g. Plastic-108) this process may lead to the acidification of the shallow groundwater (Bottomley *et al.* 1986), since the soils in headwater areas on the shield are often very shallow and groundwater reservoirs are very small.

Much lower pH values (~0.5 units) were observed downstream of a conifer swamp (Plastic-1) than upstream (Plastic-108) despite similar new water fractions (Table 1). There are two possible sources of H^+ ions measured in runoff below the swamp; direct inputs from meltwaters on the swamp or internal H^+ release within the swamp. The mass H^+ mass balance shows that the H^+ output is at least 30% greater than the sum of external inputs. Even if all the snowmelt and rain water which entered the conifer swamp directly (via saturated overland flow) contributed all their acidity to the stream the biogeochemical reactions in the swamp must release additional acidity. Much of the old and new water must have taken up H^+ on its way through the swamp despite the high flow rates and short water residence times during spring runoff. LaZerte and Dillon (1984) showed that sulphate ($SO_4^{=}$) dominated the proton contributing anions during spring runoff in Plastic-1 and they concluded that organic acids can not be the main source of the H^+ supplied by the swamp. However, the exact mechanisms of this H^+ release are not fully understood yet and are currently being studied.

TABLE 1 Hydrological and chemical characteristics of spring runoff 1987.

	Plastic-108	*Plastic-1*	*Harp-5*
total spring runoff[1] *(mm)*	*208*	*178*	*204*
new water fraction[1] *(%)*	*53.7*	*49.9*	*35.5*
stream pH mean[2]	*4.85*	*4.34*	*5.35*
max[3]	*5.17*	*4.76*	*5.59*
min[4]	*4.74*	*4.27*	*5.25*

[1] *March 1 - April 30 1987*
[2] *estimated flow weighted mean for total spring runoff period*
[3] *measured during pre-melt baseflow*
[4] *measured on March 30 (peakflow)*

CONCLUSIONS

The contributions of new water alone can not explain observed differences in pH depressions in the APIOS streams. In such small watersheds, where most of the meltwater infiltrates and mixes with the shallow ground/soilwater, chemical processes within the soil play an important part in streamwater acidification. The wetland areas in those Shield catchments further increase the complexity of acidification since they appear to act as acid sources during the spring snowmelt.

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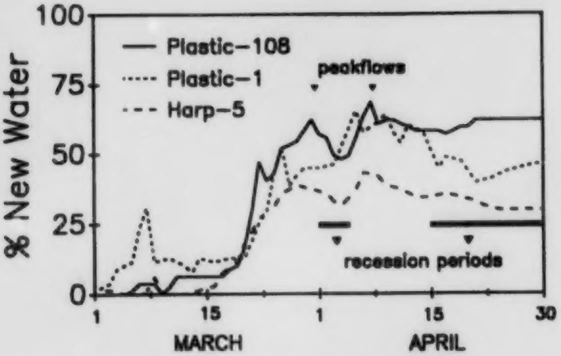

FIG.2 The contribution of new water to streamflow (in %) during spring runoff (1987) in the three catchments. Periods of peakflow and flow recession are indicated also.

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The Wilson Creek experimental watershed

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ABSTRACT Twenty-five years ago, the Wilson Creek Watershed was selected as a study site for runoff and erosion control on streams that rise on the steep Manitoba escarpment. In the ensuing period, meteorological and hydrological data were gathered and the watershed was studied to determine the runoff characteristics of an escarpmental headwater basin. Research studies considering the hydrological processes in detail; flood frequency, rainfall frequency, groundwater movement, sediment transport and snowmelt characteristics were published as graduate theses in Geography, Earth Sciences and Civil Engineering. Two headwater reservoirs and numerous channel protection works were constructed. The headwater reservoirs were found to reduce peak flood flows by 5 to 15 percent. This was insufficient to significantly reduce sediment transport or flood damage in the watershed. Channel protection works were destroyed during the maximum flood on record which occurred in September, 1975 following a 250 mm (9.84 inch) storm rainfall. Land use studies in the alluvial fan and farmlands below the escarpment indicated that a large portion of the sediment which regularly obstructs the agricultural drainage network consists of resuspended sediments from the fan area. In 1980, two experimental rockfill energy dissipation dams were constructed in the alluvial fan channel to control this recent and dominant source of sediments.

The watershed has been widely used for educational purposes. Many university theses were based on the watershed and on site workshops for a variety of disciplines are still ongoing.

RÉSUMÉ Le bassin de Wilson Creek a été choisi, il y 25 ans, comme site d'étude sur le contrôle de l'écoulement et de l'érosion dans les cours d'eau originant de l'escarpement du Manitoba. Dans les années qui ont suivi, la récolte de données météorologiques et hydrologiques et les études du bassin ont eu pour but de déterminer les caractéristiques d'écoulement d'un bassin de tête de l'Escarpement. Les recherches détaillées de processus hydrologiques tels que la fréquence des crues, la fréquence des précipitations, les déplacement de l'eau souterraine, le transport des sédiments et les caractéristiques de la fonte sont documentées dans des thèses d'étudiants gradués des départements de géographie, sciences de la terre et génie civil. Deux réservoirs d'eau de tête ainsi que de nombreux ouvrages de protection du lit et des berges ont été construits. Les réservoirs ont réduits les débits de pointe de 5% à 15%. Cette réduction était trop faible pour réduire le transport de sédiments ou les dommages dûs aux crues dans le bassin. Les ouvrages de protection ont été emportés par la crue record de septembre 1975 causée par une averse de 250 mm (9.84 po). Des études d'utilisation des terres dans la zone d'alluvions et de terres agricoles en aval de l'escarpement ont révélé que la majeure partie des sédiments qui bloquent les canaux d'irrigation étaient des sédiments de la zone d'alluvions remis en suspension. En 1980, deux empilements de roche pour la dissipation d'énergie

furent érigés dans le canal de la zone d'alluvions afin de réduire cette source récente et dominante de sédiments.

Le bassin a servi beaucoup à des fins éducatives. Il a servi de base à plusieurs thèses universitaires, et est encore le site d'ateliers portant sur une variété de disciplines.

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Determination of thunderstorm runoff in a prairie urban setting

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ABSTRACT The objective of the project was to obtain sufficient data on the relationships between urban runoff and storm intensities and durations under the conditions of Prairie towns and cities. The study relates to the much larger problem -- that of designing storm sewers for urban areas where much of the area is covered with pavement and additional storm water from new housing developments are added to the existing systems. The Idylwyld installation was one of the most detailed field studies of the general problem in North America but water quantity was not the real problem, water quality was. Although the system was quite versatile and flexible the technology to monitor water quality was not available until 1983.

RÉSUMÉ Le but du projet était d'obtenir une quantité adéquate d'information sur les relations entre l'intensité et la durée d'orages et l'écoulement d'un bassin urbain dans les Prairies. L'étude est reliée à un problème plus complexe, celui de concevoir des égouts pluviaux pour des villes où des surfaces importantes sont déjà pavées, et où les égouts pluviaux de nouveaux développements son racordés aux réseaux existants. L'installation d'Idlwyld a constitué l'une des études de terrain les plus détaillées en Amérique du Nord, malgré que le vrai problème ait été la qualité de l'eau et non la quantité. Bien que le système ait été versatile et flexible, la technologie de contrôle de la qualité de l'eau n'a été disponnible qu'en 1983.

INTRODUCTION

The construction of the Idylwyld Underpass on the north side of Saskatoon was completed in 1969. This was the first freeway underpass in Saskatchewan. During the design of the Idylwyld Underpass, the consulting engineers could not fin d suitable Prairie data on storm intensities, duration and return periods for the period before 1966. So the engineers had problems designing the storm drainage system. Moreover, the information that they received indicated the present design philosophy is towards using longer return periods to offset uncertainties in the expected values of storm runoff. North American cities were starting to use a 50 year return period of their drainage problems: a costly design based upon a 50 year return period probably is not justifiable for a small Prairie city. The Saskatchewan Research Council installed instrumentation after construction was completed to obtain instantaneous rainfall and storm water outflow data.

The objective of the project was to obtain sufficient data on the relationships between urban runoff and storm intensities and durations under the conditions of Prairie towns and cities. The data were to be made available to city engineers, consulting engineers, and highway engineers so that they can determine more accurately the cost/benefit for various levels of drainage and sewer design. The Saskatchewan Department of Highways and City Engineering and Sewers supported the project.

The computer was one of the first PDP-8L's off the production line. This computer enabled information to be simultaneously collected at 12 locations to the nearest 1/10 of a second. This data were from 7 rain gauges over the 7 ha watershed, one level sensor in the basement of the pump house and 4 flow meters monitoring the flow from the 1700 m^3 pumps.

WHY A RESEARCH BASIN APPROACH

The site of the underpass, with its comparatively simple storm drainage system, was instrumented to yield instantaneous rainfall and storm water outflow data. This information would be used to provide valuable information for the design of similar and more complex urban flood basins. Due to the support of the city and highways department, it was expected that the Saskatchewan Research Council could control the development in the basin and the area surrounding it.

During ten years of data collection, some 27 storms of significant intensity were recorded. The project was completed in 1981 after 10 years of complete data were collected. There is currently no research being undertaken on storm water runoff in Saskatchewan, even though there was a death due to drowning in this underpass two years after the Saskatchewan Research Council completed its work. The storm water was lifted from the underpass by pumps into a complex of sloughs. These have now been filled in and on many occasions storm water is lifted out of the underpass only to flood back in from the open storm water canal.

On occasions the data have been requested for other research agencies, such as the University of Saskatchewan for studies on the Universal Soil Loss Equation.

CONCLUSION

The study relates to the much larger problem, that of designing storm sewers for urban areas where much of the area is covered with pavement and additional storm water from new housing developments are added to existing systems. The Idylwyld installation was one of the most detailed field studies of the general problem in North America but water quantity was not the real problem, water quality was. Although the system was quite versatile and flexible because it was computer controlled we did not have the technology until 1983 to monitor water quality properly. By then, the IHD program was long over.

In addition, soon after construction was finished, detailed 'as-built' drawings were made. These drawings showed that flood routing studies were not going to be simply done in the system because of poor invert alignment of the pipe network.

Furthermore, the cost of calibrating SWIMM and other models with real-time data proved to be too expensive and no consulting companies would undertake the studies. The study was under-funded almost from the start and there was a perceived lack of relevance to the Saskatchewan scene. However, the main accomplishment of the study was the computer system and the speed of data collection. Not until the last few years are there computers which could exceed the collection speed of the PDP-8. The expertise gained in the construction and operation of this equipment gained the Saskatchewan Research Council a reputation for instrument design and data collection. The use of automated computer connection by phone was pioneered by the Saskatchewan Research Council in 1972 and expanded to satellite data re-transmission of data by voice synthesizers and alarm systems which would check incoming data for trends, high/low and standard deviation changes.

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Solute and sediment dynamics in a semi-arid, ephemeral drainage basin

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ABSTRACT Eighty to ninety per cent of the sediment load of the Red Deer River, Alberta, originates in semi-arid badland areas which cover less than 2 per cent of its 43,000 km^2 drainage basin. High erosion rates in the badlands have been confirmed by various experiments on microscale plots. A 33.7 ha drainage basin in Dinosaur Provincial Park, Alberta, was instrumented to examine the relationship between results obtained on microscale plots and the behaviour of a larger mesoscale badlands drainage basin.

Comparison of the rainfall-runoff relationship and the export of solutes and sediment at the two scale levels indicates that, despite a similarity in annual erosion rates, a change in spatial scale does cause important differences. Thus it is essential to make observations and develop theories at a spatial scale compatible with the drainage basin of interest, as possibilities for scale transference appear to be limited.

Most of the research is directed towards the identification of sources and mechanisms of routing of runoff, solutes and sediment. Three major surface units may be distinguished. Sandstone and pediment surfaces possess high runoff coefficients, and yield runoff after 2-4 mm of rainfall. Shale surfaces yield runoff after 15-20 mm of rainfall. Concentrations of solutes and sediment are significantly higher in runoff from shale surfaces than in runoff from sandstone and pediment surfaces.

Tunnel erosion features are ubiquitous in the badlands. Measurements of the discharge and solute and sediment concentrations were carried out at two tunnel outlets. Response times of the tunnel and channel systems were similar and indicate that up to 10 per cent of the total basin discharge may be routed through tunnel systems. Solute and sediment concentrations were three to four times higher in tunnel flow than in channel flow, making tunnel flow an important factor in solute and sediment routing.

Analysis of sediment concentration/discharge relationships indicates that hysteresis changes from clockwise to counterclockwise when total rainfall exceeds 5 mm. This is the threshold rainfall needed for the initiation of tunnel flow, which causes counterclockwise hysteresis due to a delayed increase in solute and sediment concentrations during a runoff event. This contrasts with the clockwise hysteresis caused by the flushing effect during the early stages of smaller rainstorms.

RÉSUMÉ De 80% à 90% de la charge en sédiments de la "Red River", en Alberta, provient des "badlands" semi-arides qui recouvrent moins de 2% de son bassin de 43 000 km^2. Les forts taux d'érosion dans les "badlands" ont été vérifiés lors de diverses expériences sur des mini-parcelles. Un bassin de 33.7 ha, dans le parc provincial de Dinosaur, Alberta, a été instrumenté dans l'intention de relier le comportement des mini-parcelles à celui d'un bassin moyen drainant les "badlands".

La comparaison entre les relations précipitations:écoulement et le transport de solutés et de sédiments aux deux échelles révèle que la

différence d'échelle entraîne des différences importantes, malgré une similitude au niveau des taux d'érosion annuels. Il semble donc important de procéder aux observations et de développer les théories à une échelle comparable à celle du bassin d'intérêt, vu que l'extrapolation des résultats d'une échelle à une autre semble problématique.

Le gros de la recherche est orienté vers l'identification des sources de l'écoulement, des solutés et des sédiments et des mécanismes qui régissent ces pertes. On peut distinguer trois types de surfaces. Les grès et les surfaces de pavés ont des coëfficients de ruissellement élevés, et génèrent un écoulement de surface après 2 à 4 mm de pluie. Les shistes, le troisième type, génèrent un écoulement de surface après 15 à 20 mm de pluie. Les concentrations en solutés et de sédiments sont significativement plus élevées dans le ruissellement provenant des schistes que dans celui provenant des grès ou des surfaces de pavés.

L'érosion en tunnel est omniprésente dans les "badlands". Des mesures de débits et de la concentration en solutés et en sédiments on été effectuées à la sortie de deux de ces tunnels. Le temps de réponse de ces tunnels est comparable à celui de cours d'eau et indique que jusqu'à 10% du débit du bassin pourrait emprunter de tels tunnels. Les concentrations en solutés et en sédiments étaient de trois à quatre fois plus élevées dans l'eau de ces tunnels que dans l'eau du cours d'eau, ce qui souligne l'importance de ces tunnels dans l'acheminement des solutés et des sédiments.

L'analyse des relations concentrations:débits indique que l'hystérèse qui trace une courbe dans le sens des aiguilles d'une montre devient à contre-sens quand la précipitation excède 5 mm. Ce seuil de précipitation correspond à celui nécessaire à la formation de l'écoulement en tunnel, avec un apport en solutés et en sédiments retardés vers la fin de l'évènement pluvieux. L'hystérèse dans le sens des aiguilles d'une montre, par contre, résulte de l'effet de chasse dans les débuts des précipitations plus faibles.

INTRODUCTION

About one-third of the 43,000 km^2 drainage basin of the Red Deer River in southern Alberta lies in the semi-arid prairie region. While this region contributes only about 13 per cent of the Red Deer River's annual discharge, it contributes about 80-90 per cent of the sediment load (Bryan & Campbell, 1986). Most of this sediment load originates in the 800 km^2 of badlands which fringe the Red Deer River on the last 300 km of its course before it joins the South Saskatchewan River. The magnitude of this localized sediment input is sufficiently large to produce a distinctive high point in the long profile of the Red Deer River (Campbell, 1977).

The high erosion rates (average ca. 3 mm y^{-1}, with peaks of 13 mm y^{-1}) in the badland areas were confirmed by various experiments on microscale plots (Campbell, 1981). Linking the results obtained on microscale plots to the sediment load of the Red Deer, however, should be done with caution because this increase in spatial scale introduces two problems. Firstly, sediment storage within the drainage network causes a discrepancy between erosion rates measured on hillslopes using microscale plots and the actual amount of material exported from a basin. This effect is reinforced by the frequent flow discontinuities occurring in semi-arid environments. Secondly, a significant portion of runoff may, on its way to the basin outlet, pass through tunnel erosion features which are ubiquitous in badland areas. Runoff routed through these features will have greatly increased concentrations of solutes and suspended sediment, so that their geomorphologic and hydrologic significance is considerable (Bryan & Harvey, 1985). Microscale plots, however, do not allow evaluation of this significance.

In 1981 the 33.7 ha research basin was instrumented in cooperation with the Department of Geography, Scarborough College, University of Toronto. The original objective was to investigate how information obtained on microscale plots could be spatially extrapolated to help understand the behaviour of a typical mesoscale badlands drainage basin. Since then research on various geomorphological and hydrological subjects has been carried out in the basin.

Several factors influenced the decision to instrument this particular basin. Firstly, the basin is located in the restricted access area of Dinosaur Provincial Park. This means that disturbance of the basin is minimal, which enables studying the basin in its natural state. Secondly, because of the restricted access, damage to expensive and delicate equipment by vandalism is avoided. Thirdly, the basin is easily accessible. Sampling sites are located at a ten minutes walking distance from the nearest road. This allows rapid access so that when rainfall occurs observations and sampling can be carried out during even the earliest stages of flow.

A drainage basin is a fundamental geomorphologic unit. This makes the drainage basin approach highly significant for geomorphological research. It allows the investigation of the response of an integrated geomorphologic system to a variety of conditions, and of the interaction of its subsystems. These aspects are important from the viewpoint of both long term landform evolution and present day management problems. The following research projects have been or are currently being carried out in the basin.

IDENTIFICATION OF SOURCES AND PATHWAYS OF RUNOFF, SOLUTES, AND SEDIMENT

Research objectives

This project is designed to gain insight into the spatial distribution of source areas and clarify mechanisms of routing of runoff, solutes and sediment in a semi-arid, ephemeral, mesoscale drainage basin. Such information contributes to the knowledge of processes of runoff generation in semi-arid environments, and allows the identification of threshold conditions determining different modes of drainage basin behaviour. In addition, past research has indicated that in many cases a partial area model is applicable for sediment load, and that source areas of runoff and sediment load are not always coincident. A direct consequence is that the calculation of erosion rates within a basin by taking the sediment load at the basin outlet and averaging it over the basin area becomes an exercise in simplistic speculation (Campbell, 1977, p.183). This makes the identification of these source areas essential, not only for practical purposes, such as water harvesting or the evaluation of erosion control practices, but also to assess the consequences of the spatial distribution of sediment sources for the geomorphological evolution of a drainage basin.

Results and conclusions

Simulated rainfall experiments on a variety of microcatchments ranging in size from 10 to 30 m^2 provide insight into the response to rainfall of the different badland surfaces. Results have been presented in detail elsewhere (e.g. Bryan et *al.*, 1984) and are only summarized here. The typical simulated rainstorm had a 29 mm h^{-1} intensity and a 30 min duration. At the nearest meteorological station, located in Brooks, a natural rainstorm with these characteristics has a two year return period. During the simulated storms vegetated areas did not produce runoff. Sandstone and pediment surfaces, on which water infiltrates only a few millimetres, produced runoff after at most 2-4 mm of rainfall. Shale surfaces, which are covered by a weathering layer of loose aggregates (popcorn) produced runoff after about 15-20 mm of rainfall (Campbell, 1987). Detailed studies of material properties indicated that weakly crystalline gels released by weathering of the dominantly montmorillonite clay minerals acted as a sealant, reducing infiltration on sandstone and pediment surfaces and, to a lesser extent, also on shale surfaces. The three surface types also show varied response with respect to the release of solutes and sediments (Bryan *et al.*, 1984). In summary, solute and sediment yields were significantly higher for shale surfaces than for sandstone and pediment surfaces. In addition, sandstone and pediment surfaces exhibited an initial flushing effect, followed by a gradual decline in solute and sediment concentrations as the experiment progressed. On shale surfaces this effect was absent.

Monitoring of two tunnel systems by Bryan & Harvey (1985) indicated that response times of these systems are similar to channel response times, so that tunnel flow contributions cannot be distinguished in the stream hydrograph. They also showed that tunnel flow may contribute up to 10 per cent of the total basin discharge. The significance of tunnel flow, however, lies in the fact that solute and sediment concentrations of tunnel flow are typically three to four times higher than normally found in channel flow. Thus, while hydrologically relatively insignificant, tunnel flow is an important factor in solute and sediment routing in a badland environment.

Analysis of sediment concentration/discharge relationships indicates two modes of drainage basin behaviour related to tunnel flow. During rainstorms of less than about 5 mm, the sediment concentration/discharge relationship displays clockwise hysteresis, indicating exhaustion of the sediment supply. During these relatively small rainstorms runoff is generated on the rapidly responding sandstone and pediment surfaces only. This restricts the sediment sources within the basin to these two units, and to the channel and tunnel systems forming the drainage network. Sediment available in the channel and tunnel systems is, except possibly under extreme circumstances, not supply-limited. The sandstone and pediment surfaces, however, do act as supply-limited sediment sources as sediment and solutes accumulated on these surfaces during dry periods are flushed away during the initial stages of runoff. In addition, transmission losses within the tunnel systems are initially high, preventing significant contributions to the sediment load at the basin outlet by runoff picking up solutes and sediment within these systems.

During rainstorms larger than 5 mm, drainage basin behaviour is markedly different. The sediment concentration/discharge relationship exhibits counterclockwise hysteresis, indicating an increase in sediment supply during the storm. This increase is thought to be caused by solutes and sediment picked up within the tunnel system by runoff generated on pediments and sandstones draining to the basin outlet via the tunnel systems. The 5 mm of rainfall is interpreted as the threshold amount necessary to overcome initial transmission losses within the tunnel system, and to initiate spatially continuous flow in the tunnels.

SPATIAL SCALE AND DRAINAGE BASIN RESPONSE

Research objectives

One of the fundamental problems in geomorphology, and hydrology, is how to relate small scale process measurements to the behaviour of a landscape system at a very much larger scale. The problem lies in the fact that this increase in spatial scale does not merely involve an increase in spatial dimensions, but instead implies new variables, new relationships, and often leads to the identification of new problems. Observations were made under natural rainfall of the behaviour of a series of drainage basins ranging in size from about 2000 m^2 to 337,000 m^2, in order to assess the effect of spatial scale on the rainfall-runoff relationship and the export of solutes and sediment from a semi-arid, ephemeral drainage basin. These results were compared to detailed data collected from simulated rainfall on 1 m^2 plots.

Results and conclusions

Calculation of the annual basin-wide erosion rate based on the sediment load exported from the total basin yielded a value of about 3 mm y^{-1} (Bryan & Campbell 1986). This corresponds remarkably well to the value of 4 mm y^{-1} found in a 10 year study of denudation rates on microscale plots (Campbell 1981). This similarity in denudation rates between microscale plots and a mesoscale basin notwithstanding, differences in behaviour do exist between different scales.

An example can be found in the relationship between total rainfall and drainage basin behaviour. At the microscale (1 m^2) the threshold amount of rainfall for runoff generation on the different surfaces is of critical importance. At the mesoscale (337,000 m^2), however, these amounts of rainfall do not signify radical changes in basin behaviour. Instead, at the mesoscale an important threshold is the amount of rainfall (5 mm) corresponding to the initiation of tunnel flow. Thus the increase in spatial scale has two effects. Firstly, thresholds defined at the microscale are not associated with mesoscale thresholds, so that extrapolation from the microscale to the mesoscale is not as straight-forward as often is assumed. Secondly, at the mesoscale, elements exist which are non-existent at the microscale, e.g. a tunnel system. The behaviour of the mesoscale basin is dominated by such elements, rather than by the microscale components it contains. It appears that it is essential to make observations and develop theories at a spatial scale compatible with the drainage basin of interest, in order to avoid the problems associated with extrapolating from one scale to another.

ACKNOWLEDGEMENTS

Research in Dinosaur Provincial Park was made possible by permission from Alberta Recreation and Parks and by the cooperation of their staff in Dinosaur Park. It was supported by operating grants from NSERC to Ian Campbell and Rorke Bryan. A travel grant from the Faculty of Graduate Studies and Research and the Alma Mater Fund at the University of Alberta to Dirk de Boer is gratefully acknowledged.

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Patterns of nutrient yield in spruce-fir and aspen-grassland research basins in Alberta

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ABSTRACT Marmot and Streeter research basins, selected during 1962-1964 for hydrologic research along the eastern slopes of the Rocky Mountains, represent spruce-fir and aspen-grassland vegetation types in southwestern Alberta. Differences in streamflow and concentrations of dissolved solids account for different yields on an equal area basis in the two basins: 27 and 69 t km^{-2} y^{-1} for Streeter and Marmot respectively. The mean yield of main constituents in Marmot during 1972 was Ca, 18 406; Mg, 4 940; Na, 321; K, 218; HCO_3, 72 291; SO_4, 5 242; SiO_2 2 013; and the sum of constituents, 66 567 kg km^{-2} y^{-1}. As vegetation provides the main avenue for exercising a modifying influence (geologic, edaphic, topographic, and climatic factors are more or less fixed features of a catchment) it was hypothesized that maximizing vegetation cover was likely to minimize nutrient losses. However, this could not be tested for the treatments applied to the two basins.

RÉSUMÉ Les bassins de Marmot et Streeter ont été choisis entre 1962 et 1964 dans le contreforts des Rocheuses pour fins de recherche en hydrologie. Ces deux bassins représentent deux types de végétation du sud-ouest de l'Alberta, soit la forêt d'épinettes et de sapins, et la prairie à tremble. La quantité de solides dissous dans l'écoulement de Streeter et de Marmot était de 27 et 69 t km^{-2} y^{-1} respectivement, cette différence étant dûe à la fois aux différences de débits et de concentration. En 1972, les ruisseau drainant le bassin de Marmot a transporté 72 291 kg de HCO_3, 18 406 kg de Ca, 5 242 kg de SO_4, 4 940 kg de Mg, 2 013 kg de SiO_2, 321 kg de Na, et 218 kg de K. Comme les facteurs climatiques édaphiques, géologiques et topographiques sont plus ou moins constants, on ne peut modifier ce régime qu'au travers de la végétation. L'hypothèse a donc été proposée qu'en maximisant le couvert végétal, la perte d'éléments nutritifs serait minimisée. Cependant, les traitements appliqués aux deux bassins ne permettaient pas de tester cette hypothèse.

INTRODUCTION

Forest and range hydrology research on the east slopes of the Rocky Mountains, where most of the flow to Saskatchewan River originates, was initiated under the joint provincial-federal Alberta Watershed Research Program. Initially two watersheds, Marmot Creek and Streeter Creek, were selected in 1962-1964. The basins represent the spruce-fir forest and aspen-grassland vegetation of southwestern Alberta. Streeter basin is located in Porcupine Hills and Marmot basin is near Kananaskis where the 1988 Winter Olympic Games were held.

Sediment and water quality samples were collected from 1966 to 1972. The chemical analyses were conducted and the results made available in annual compilations by the Water Survey of Canada.

RESULTS OF CHEMICAL AND HYDROLOGIC ANALYSES

Marmot Basin

Ca, Mg, Na, K are the main cations; the main anions are HCO_3, SO_4, and SiO_2. In 1972 the mean yield (kg km^{-2} y^{-1}) of these constituents was estimated as Ca, 18 406; Mg, 4 940; Na, 321; K, 218; HCO_3, 72 291; SO_4, 5 242; and SiO_2, 2 013 (Singh & Kalra 1984). The yield of the sum of constituents, which included the above ions and F, Cl, NO_3, and CO_3 equivalent of HCO_3, was computed as 66 567 kg km^{-2} y^{-1}. Increase in solute yields is usually directly proportional to the increase in streamflow. As most of the streamflow in this basin occurs during the months of May, June, and July, these also are the months with maximum solute yields. For unit increase in streamflow, HCO_3 and Ca showed the maximum rate of increase in yield, SO_4 and Mg showed moderate, and SiO_2, Na and K the minimum rate of increase in yield.

Streeter Basin

The results obtained from streamflow and concentration of dissolved solids (as determined by the residue-on-evaporation method) indicate that the mean yield for 1967 to 1970 was 445 kg d^{-1} (Singh, 1976). The maximum yield of geochemical constituents occurred in the months of April, May, June and July. Snowmelt on this basin occurs as early as April.

DISCUSSION

Differences in streamflow and concentrations of dissolved solids in Marmot and Streeter watersheds account for their different constituent yields on an equal area basis. The total constituent yields (t km^{-2} y^{-1}) were estimated as 27 for Streeter, compared to 69 for Marmot. By way of comparison, the nutrient yields for the two pasture and forest catchments in the United Kingdom (Wales) were 45 and 77, respectively (Oxley, 1974). The difference in the rates of chemical degradation for the Welsh catchments was much higher than the difference in suspended sediment yields (13 and 11 t km^{-2} y^{-1}, respectively).

It was hypothesized that conservation practices aimed at maximizing vegetation cover were likely to minimize nutrient losses from subalpine catchments such as Marmot, because of reduced streamflow, and direct uptake of nutrients and storage by vegetation. Further, the dilution caused by increased streamflow as a result of vegetation removal was likely to mask the nutrient depletion effects from a site if judged by concentration values alone. The results of this analysis showed that nutrient concentrations and yields must be considered in conjunction with each other to determine the extent of nutrient removal from headwater watersheds and their subsequent accumulation in downstream water bodies and sites.

As geologic, edaphic, topographic and climatic factors are more or less fixed features of a watershed, only vegetation provides the main alternative for exerting a modifying influence. For example, vegetation clearing or manipulation is likely to have an impact on soil temperature. Since temperature affects the rates of chemical reactions and weathering, increased soil temperature is likely to accelerate the activity of microbes and a rapid disappearance of the organic fraction. Increased leaching and higher streamflows due to clearcutting are likely to cause a greater yield and export of nutrients from forest watersheds.

Unfortunately, the treatments applied on Marmot and Streeter basins could not be tested for the above-mentioned hypotheses. The treatment effects relating to nutrient release and solute yields therefore remain unknown for the most part. However, the research on these basins provided a wealth of baseline information on the concentration and patterns of yield of chemical constituents.

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Forest harvesting and sediment yield in the Tri Creeks basin[1]

G. VAN DER VINNE & D. ANDRES
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ABSTRACT The Tri Creeks basin study was initiated in 1965 to determine changes to Alberta foothills streams which occur following forest harvesting. The objective of the portion of the study described herein is to assess the changes in the annual sediment yields in the two affected streams, Wampus Creek and Deerlick Creek, with respect to Eunice Creek, a stream unaffected by forest harvesting.

The monitoring of annual streamflow and sediment yields, not including winter flows, began in 1968 and continued until 1984. On a unit area basis, Deerlick Creek and Eunice Creek deliver about 12 t km^{-2}, while Wampus Creek delivers twice that amount. Double mass analysis indicates that sediment yield increased following road construction, mainly, and somewhat following harvesting in both Wampus Creek and Deerlick Creek basins. Within the context of natural variability, this has a limited impact on the streams.

RÉSUMÉ L'étude du bassin de Tri Creeks a débuté en 1965 avec comme objectif de déterminer l'effet de la coupe sur les ruisseaux des contreforts de Rocheuses. L'obfectif de la portion de cette étude décrite ici était d'évaluer les changements de charge en sédiments dans Wampus Creek et Deerlick Creek, les deux ruisseaux affectés par la coupe, par rapport à Eunice Creek, un ruisseau témoin.

Les débits et les charges annuels en sédiments, excluant les débits d'hiver, ont été mesurés de 1968 à 1984. Les charges annuelles en sédiments étaient d'environ 12 t km^{-2} pour Deerlick Creek et Eunice Creek, et du double pour Wampus. L'analyse double-cumul indique que les charges en sédiments ont augmenté surtout suite à la construction des route, et faiblement suite à la coupe, et celà sur les deux bassins traités. Pris dans la perspective de la variabilité naturelle, ces effets n'ont eu que peu d'impact sur les ruisseaux.

INTRODUCTION

The Tri Creeks Watershed Study was initiated in 1965, under the auspices of the International Hydrologic Decade (IHD), by the Department of Lands and Forests, as part of the Alberta Watershed Research Program. The Alberta Research Council became involved as part of a multi-disiplinary group established to pool the expertise required for the study. Although there were a number of objectives in this study, only one of the main objectives is discussed herein. This objective is to determine the effects of forest harvesting on basin sediment yield.

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[1] Alberta Research Council Contribution Series Number 1581.

The Tri Creeks watershed, which is comprised of three small sub-basins, has a total basin area of about 59 km^2 and is situated about 40 km southwest of Hinton, Alberta at 53°09′ north latitude and 117°15′ west longitude. Of the three sub-basins, Wampus Creek is the largest at approximately 28 km^2 followed by Eunice Creek and Deerlick Creek at about 16 km^2 and 15 km^2 respectively. The elevation ranges from a maximum of 1707 m to a minimum of 1262 m. The climate is humid, micro-thermal, and subarctic and the mean annual precipitation is 707 mm with 36% of this falling as snow. The vegetation consists of subalpine forest with the main species being Lodgepole pine and Black spruce. The soil is weathered glacial till.

TREATMENT

Forest harvesting was done in both the Wampus Creek and Deerlick Creek basins, while the Eunice Creek basin was left uncut. In the fall of 1974, the main haul road was constructed from the mouth of Deerlick Creek, along Deerlick Creek for about 2 km, and then into the lower Wampus Creek basin. Forest harvesting began in November, 1977 along lower Wampus Creek and progressed upstream each winter until, in the spring of 1983, 39% of the basin had been clear-cut in a number of large cutblocks. Strips of trees were left along the streambanks to buffer the creek from harvesting activities. Forest harvesting began in lower Deerlick Creek in the fall of 1981. By the spring of 1984, a number of large cutblocks, comprising 41% of the basin area, had been clear-cut. Scarification, done between 1979 and 1984, disturbed the upper soil layer in the clear-cut areas in both treated basins.

DATA COLLECTION

Water Survey of Canada water level recorders near the mouth of each creek operated during the open water period each year from 1968 to 1985 to collect streamflow data. Rating curves were developed from periodic discharge measurements during the summer months. To measure sediment yield, depth integrated sediment concentrations were obtained periodically over the open water season. Overall, fewer measurements were taken in the early years of the study, but, on a yearly basis, more frequent measurements were taken during peak flow events. Daily sediment yields were obtained by multiplying the daily mean discharge and the daily mean sediment concentration. These daily yields were then summed to obtain the sediment yield for the open water season.

ANALYSIS

A relatively consistent relationship between sediment yield and water yield is evident for all three basins (Fig.1). Sediment yield was found to vary with the third power of water yield when the basins were in their natural state. There is no indication in Fig.1 that this relationship was significantly different after the disturbances related to forest harvesting occurred.

In Fig.2, double mass curves are used to compare the sediment yields of Wampus Creek and Deerlick Creek to those of Eunice Creek. An increase in the slope of the Deerlick double mass curve from 1974 to 1976 indicates a relative increase in sediment yield in Deerlick Creek during this period. The increase was likely caused by the construction of the main haul road along Deerlick Creek in 1974. No corresponding increase in slope can be seen in the Wampus

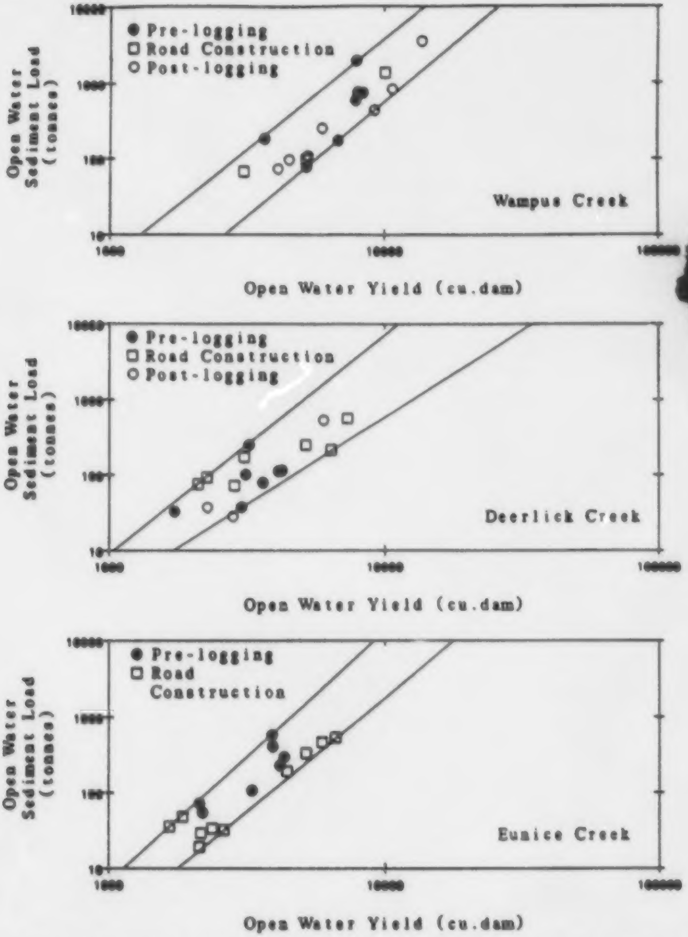

FIG.1 Comparison of the open water sediment yield with the open water yield for Wampus, Deerlick, and Eunice Creeks (1968-1984).

double mass curve, likely because very little of the road construction in this basin occurred near the stream.

In 1977, the sediment load in Deerlick Creek was near its pre-disturbance norm again, but from 1978 to 1984, the sediment yield was again greater relative to that of Eunice Creek. Road use associated with harvesting in Wampus Creek basin probably contributed to the increase. There is an indication of a slight increase in sediment yield after harvesting began in the Deerlick Creek basin in 1982 but there is not enough years of data available to analyze this period properly.

According to the Wampus double mass curve, an increase in Wampus Creek sediment yield compared to that of Eunice Creek occurred in both 1980 and 1981. This increase was likely the result of a large water yield in 1980. Wampus Creek produces, on average, twice the water yield of Eunice Creek so the logarithmic relationship between water yield and sediment yield (Fig.1) results in a disproportionate increase in the sediment yield of Wampus Creek. Hence, the appearance of a substantial increase in the sediment yield of the [illegible]ted basin. The large flood in 1980 may have produced more bank erosion [illegible] usual and the destabilized banks may have continued to erode and produce increased sediment yield in 1981. However, the effects of forest harvesting [illegible]uld not be separated from the natural erosion processes.

CONCLUSIONS

A consistent relationship between sediment yield and water yield was observed throughout the study period. Road construction and road use are likely the major causes of increased sediment yield in Deerlick Creek. A

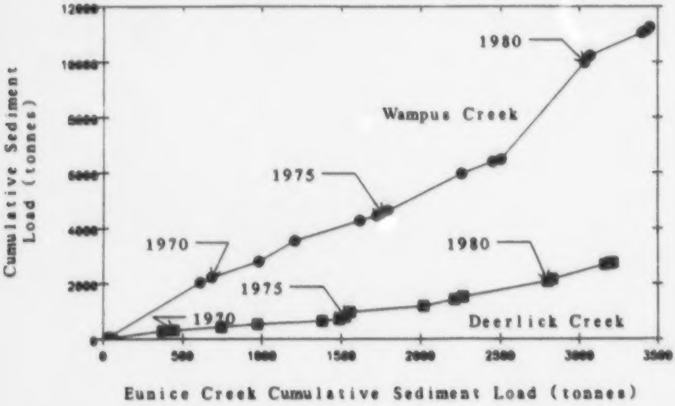

FIG.2 Double mass curves of open water sediment yields between Wampus, Deerlick, and Eunice Creeks (1968-1984).

major flood was associated with the largest increase in sediment yield in Wampus Creek. There were no significant effects on sediment yield apparent from aspects of forest harvesting other than road construction and use, although there were indications of slight increases after logging but not enough years of data were available to determine this conclusively.

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Forest harvesting and water yield in the Tri Creeks basin[1]

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ABSTRACT The Tri Creeks basin study was initiated in 1965 to determine changes to Alberta foothills streams which occur following forest harvesting. The objective of the portion of the study described herein is to assess the changes in the annual water yields in the two affected streams, Wampus Creek and Deerlick Creek, with respect to Eunice Creek, a stream unaffected by forest harvesting.

The monitoring of annual precipitation and streamflow, not including winter flows, began in 1968 and continued until 1985. The average open water yield from the three basins varied between 216 mm and 253 mm, or about 30% to 36% of total annual precipitation. Linear regression of water yield and precipitation data indicated an increase in water yield occurred in the affected basins after logging commenced. This was also apparent when a comparison of basin water yields was done using double mass analysis. Data from the treatment phase was included in the correlation between change in water yield and the amount of basin area harvested. An increase in water yield of 17% was found after 39% of the area of Wampus Creek basin was harvested while an increase in water yield of 27% was found after 41% of the area of Deerlick Creek basin was harvested.

RÉSUMÉ L'étude du bassin de Tri Creeks a débuté en 1965 avec comme objectif de déterminer l'effet de la coupe sur les ruisseaux des contreforts de Rocheuses. L'obfectif de la portion de cette étude décrite ici était d'évaluer les changements de débits dans Wampus Creek et Deerlick Creek, les deux ruisseaux affectés par la coupe, par rapport à Eunice Creek, un ruisseau témoin.

Les mesures des précipitations et des débits, excluant les débits hivernaux, ont été effectués de 1968 à 1985. Les débits ainsi mesurés allaient de 216 mm à 253 mm, soit de 30% à 36 % de la précipitation annuelle. Une analyse des données de débits et de précipitation par régression linéaire indique un accroissement des débits suite à la coupe, accroissement aussi évident sur une courbe double-cumul. Les données pré-traitement out été incluses dans une analyse de corrélation entre l'accroissement des débits et la superficie coupée. Sur le bassin de Wampus Creek, une coupe de 39% de la superficie a causé une augmentation des débits de 17%, tandis que sur Deerlick, une coupe de 41% a causé une augmentation de 27% dans les débits.

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[1] Alberta Research Council Contribution Series Number 1580.

INTRODUCTION

The Tri Creeks Watershed Study was initiated in 1965, under the auspices of the International Hydrologic Decade (IHD), by the Department of Lands and Forests, as part of the Alberta Watershed Research Program. The Alberta Research Council became involved as part of a multi-disciplinary group established to pool the expertise required for the study. Although there were a number of objectives in this study, only one of the main objectives is discussed herein. This objective is to determine the effects of forest harvesting on basin water yield.

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TREATMENT

Forest harvesting was done in both the Wampus Creek and Deerlick Creek basins, while the Eunice Creek basin was left uncut. In the fall of 1974, the main haul road was constructed from the mouth of Deerlick Creek, along Deerlick Creek for about 2 km, and then into the lower Wampus Creek basin. Forest harvesting began in November, 1977 along lower Wampus Creek and progressed upstream each winter until, in the spring of 1983, 39% of the basin had been clear-cut in a number of large cutblocks. Strips of trees were left along the streambanks to buffer the creek from harvesting activities. Forest harvesting began in lower Deerlick Creek in the fall of 1981. By the spring of 1984, a number of large cutblocks, comprising 41% of the basin area, had been clear-cut. Scarification, done between 1979 and 1984, disturbed the upper soil layer in the clear-cut areas in both treated basins.

DATA COLLECTION

To measure precipitation, readings from a network of seven Sacramento Storage gauges were taken each year in May and October from 1968 to 1985. Data was converted to basin values using the Thiessen polygon method. Water

Water Survey of Canada water level recorders near the mouth of each creek operated during the open water period each year from 1968 to 1985 to collect streamflow data. Rating curves were developed from periodic discharge measurements during the summer months.

ANALYSIS

Basin water yields varied considerably from year to year when the basins were in a natural state. While most of this variation was due to changes in annual precipitation (Fig.1), some deviations may have been caused by a lack of winter flow records. Water yields in years after forest harvesting began tended to be higher relative to annual precipitation than those yields predicted by regression analysis of the pre-logging data. Double mass

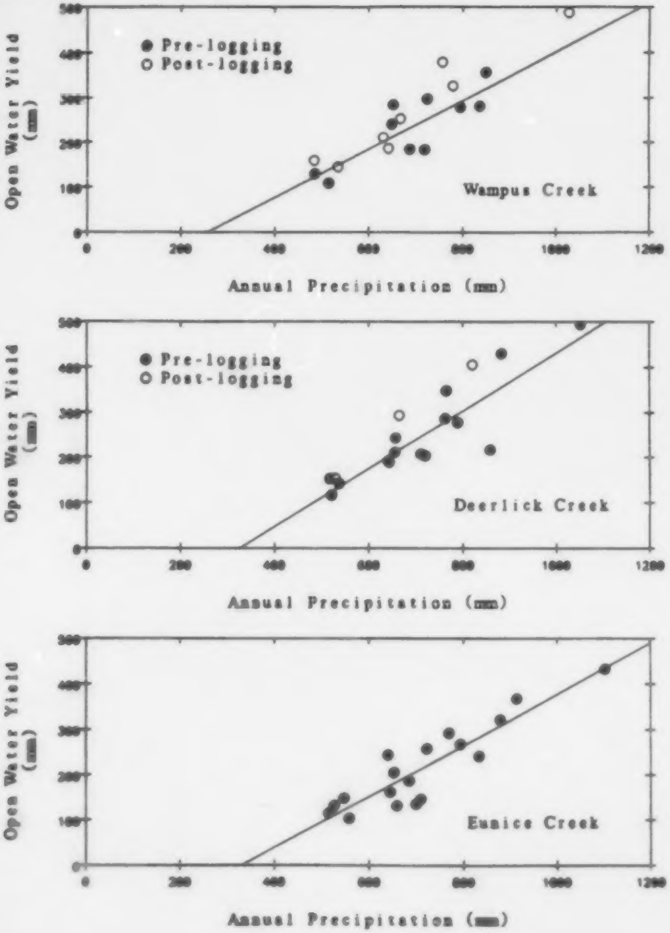

FIG.1 Comparison of open water yield with annual precipitation Wampus, Deerlick, and Eunice Creeks (1968-1985).

analysis was used to compare Wampus Creek and Deerlick Creek water yields with those of Eunice Creek (Fig.2). These cumulative curves of water yield exhibit increases in slope after logging commenced, indicating a relative increase in water yield for the basins in which forest harvesting occurred.

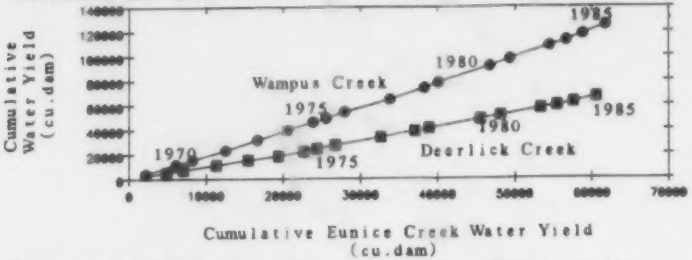

FIG.2 Double mass curves of open water yields on Wampus, Deerlick, and Eunice Creeks (1968-1985).

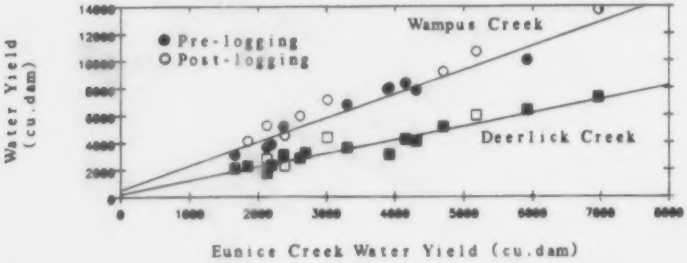

FIG.3 Comparison of open water yields on Wampus, Deerlick, and Eunice Creeks (1968-1985).

Linear regression analysis of the pre-logging water yields showed that the ratios of water yields between the basins is relatively constant (Fig.3). If the Eunice Creek water yield is known, the water yields for the other two basins could then be estimated using these yield ratios. The actual water yields in both the logged basins tended to be higher than the estimated yields, after logging took place. Deviations from these estimated values were plotted against cumulative basin area logged for both Wampus Creek and Deerlick Creek (Fig.4). A trend of increased yield with increased area logged is shown for both basins. Considerable amount of scatter occurred in this data but the slopes of the best fit lines were found to be significantly different from zero at a 1% level of significance for Wampus Creek basin and a 2% level of significance for Deerlick Creek basin.

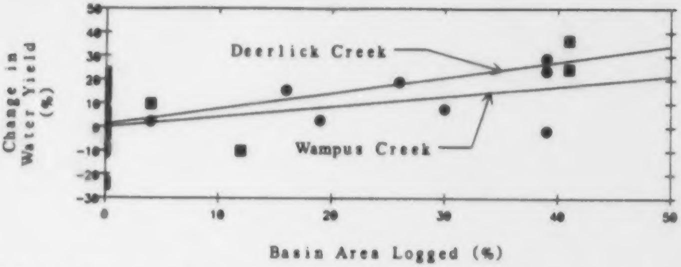

FIG.4 Change in open water yield with the percentage of basin logged in Wampus and Deerlick basins.

CONCLUSIONS

A trend of increased water yield was observed after clearcutting occurred. An increase in water yield of 17% was found in Wampus Creek after 39% of the basin had been clear-cut, and the increase in yield in Deerlick Creek was 27% after 41% of the basin was clear-cut. Differences in treatment between the two basins may have contributed to the differences in response, but the data was highly variable, so it was no surprise that the two values were different. Perhaps more accurate results could have been obtained if the harvesting had been done over one winter and the number of post-harvest years had been similar to the number of pre-harvesting years.

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Opportunistic use of hydrologic data to assess CFS-WRENSS for forestry interpretations in south central B.C.

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ABSTRACT The WRENSS procedure is a technique for evaluating the effects of timber removal on water resources. A modified version of the hydrology portion of this procedure (CFS-WRENSS) was assessed for application in south central British Columbia through the opportunistic use of hydrologic data available for the Camp Creek watershed. When compared to the results obtained through the standard paired basin approach, this procedure closely predicted the change in average annual water yield (mm) following timber removal from 27% of the watershed. However, differences in average annual water yield generated by each approach resulted in an estimated increase in water yield over predicted "no harvest" yields of 10% by CFS-WRENSS compared to 24% by the standard paired basin approach. The need for regional research basins to provide local process oriented data is clearly demonstrated. Such data would prove useful in the adaptation of computer procedures such as CFS-WRENSS for local forestry application.

RÉSUMÉ La procédure "WRENSS" est une technique pour l'évaluation des effets de la coupe sur les ressources hydriques. Nous avons évalué la possibilité d'appliquer une version modifiée de la portion hydrologique de cette procédure (CFS-WRENSS) dans le centre-sud de la Colombie Britannique grâce à la disponibilité des données hydrologiques du bassin de Camp Creek. Comparativement aux résultats obtenus par la méthode des bassins jumelés, la procédure a prédit avec assez d'exactitude les changements de débits annuels suite à une coupe rase sur 27% du bassin. Cependant, à cause d'une différence dans l'estimation des débits annuels générés par chaque approche, l'accroissement estimé des débits par rapport aux débits attendus si la coupe n'avait pas eu lieu était de 10% selon CFS-WRENSS et de 24% selon l'analyse des bassins jumelés. Ceci illustre clairement le besoin en bassins expérimentaux régionaux dans le but de fournir des données locales sur les processus hydrologiques. De telles données serviraient à adapter des procédures informatisées telles que CFS-WRENSS aux applications forestières locales.

INTRODUCTION

Where water is identified as a priority for the supply of domestic and irrigation needs, forest managers express concern over the impact of timber removal on water yield. When dealing with this concern, managers in south-central British Columbia (B.C.) rely on research findings from experimental watersheds located elsewhere and on existing hydrologic data to provide local information regarding potential impacts (Cheng *et al.* 1988).

To assist in scheduling timber harvest to protect water resource values, results from watershed research have been incorporated into computer models. One model considered for use in southern B.C. is the WRENSS procedure (USDA Forest Service 1980). The water yield portion of this procedure has been developed by the Canadian Forest Service (CFS) into a menu driven system for personal computer use (CFS-WRENSS) as described by Bernier (1986). The simplicity, and supposed objectivity, of applying this computer procedure to evaluate harvesting strategies makes its use very appealing. However, since this model was developed elsewhere, and since data from local long-term watershed studies are yet unavailable to verify its output, the applicability of this procedure for south central B.C. is questionable.

The objective of this project was to ascertain the reliability with which the CFS-WRENSS procedure predicts the effect of forest harvesting on water yield for a watershed in south central B.C. This was done by comparing the results to those generated using the standard method of evaluating changes in water yield - the paired basin approach (Hewlett 1971).

METHODS

The basin used in this evaluation was the 34 km^2 Camp Creek watershed (Fig.1). The gauge in this basin was established by Water Survey of Canada in late 1965 as part of the IHD program. The data is described as opportunistic since Camp Creek was gauged for other objectives than to evaluate the effect of forest harvesting. Timber harvesting commenced in 1976 following the discovery of a pine beetle infestation. For the purposes of the model, harvesting was assumed to effect water yield commencing in the 1976/77 water year. A summary of yearly harvesting in the watershed is presented in Fig.2.

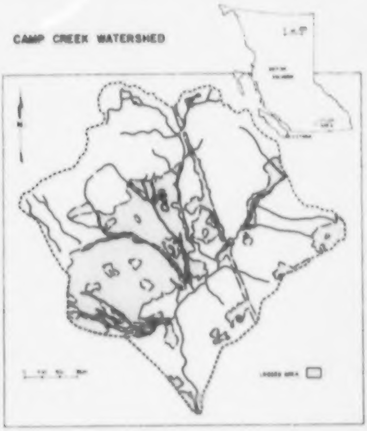

FIG.1 The location of Camp Creek in south central B.C. and the extent of forest harvesting in the watershed.

CFS-WRENSS Assessment

Our approach to evaluating CFS-WRENSS was to run the model for each year in which corresponding water yield information existed. Input requirements included basin description, basin climate, vegetation description and a treatment description. The basin climate - precipitation, windspeed and the number of days with snow - were variables which we could control to influence output. Consequently, to provide realistic inputs to the procedure, we evaluated precipitation data from several nearby locations. The station at Peachland Brenda Mines explained 71% (P<.005) of the variation in Camp Creek yield and was therefore used as the source of precipitation values to run the model. Since windspeed plays an important role in direct snowpack evaporation in the model (Bernier 1986), we chose to run the procedure at two different windspeeds, 0 and 3 m/sec. A windspeed of 3 m/sec represents conditions that might be expected on site (AES, Kelowna, pers. comm.) whereas a windspeed of 0 m/sec turns off snowpack evaporation in the model. The number of days with snowcover was estimated from nearby snow course data. Other information necessary to run the model was obtained from forest inventory records and through a computerized mapping system. Baseline water yields were obtained by running the model annually for the study period assuming no treatment. Water yield was then re-calculated from 1976/77 onward with treatments corresponding to the yearly harvest. The values were then compared to determine the change in yield as a result of timber harvest.

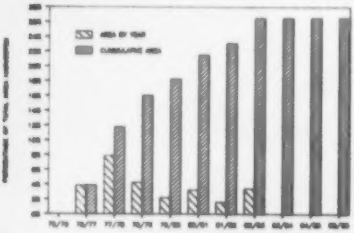

FIG.2 Percentage of the total area of Camp Creek watershed harvested by year.

Paired basin approach

Camp Creek was paired with an adjacent, 40.7 km^2, unlogged watershed - Greata Creek - thereby providing an adequate control. The relationship between water yield from Greata Creek (dependent) and Camp Creek (independent) for the pre-logging period was used to predict the yield from Camp Creek following timber removal. The pre- and post-harvesting relationship between these two watersheds is illustrated in Figure 3. The change in yield as a result of harvesting was used to assess the change predicted by CFS-WRENSS.

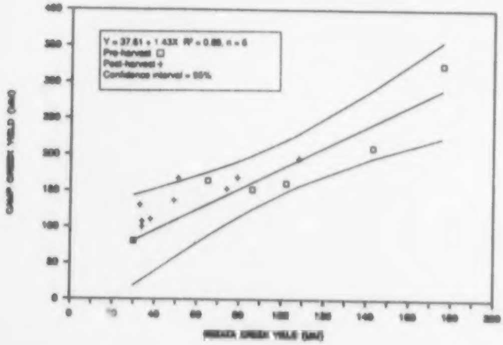

FIG.3 The relationship between Greata Creek (control) and Camp Creek annual water yield.

RESULTS

The CFS-WRENSS assessment of up to 27% timber removal from Camp Creek indicated an average water yield increase of 23 mm using a windspeed of 0 m/sec in the model. This represented a 10% increase over procedure generated water yield assuming no harvest. When a windspeed of 3 m/sec was specified, the procedure predicted an average increase of 9 mm which represented only a 4% increase. This difference reflects the *in situ* sublimation loss attributable to windspeed.

By comparison, the paired basin approach suggested a similar average post-harvest water yield increase of 24 mm. This, however, represented a 24% increase over predicted yield if the basin was not harvested. With the exception of one year this apparent increase is not significant at the 95% confidence level (Fig.3).

The results of our yearly runs with CFS-WRENSS are presented in Table 1 along with the increases generated from the paired basin approach. With the exception of one pre-harvest and one post-harvest water year, there was no significant difference at the 95% level between the WRENSS yield and with yield measured in Camp Creek, based on a preharvest calibration of the two (Fig.4). The two significantly different years represent Camp Creek water yield to precipitation ratios that were higher than the other years used in the analysis.

DISCUSSION

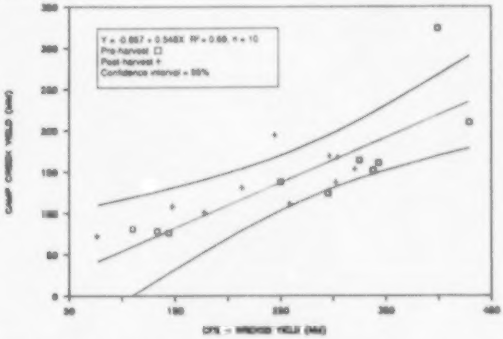

FIG.4 The relationship between CFS-WRENSS predicted and measured water yields from Camp Creek.

Our results indicate the CFS-WRENSS procedure closely predicted the increase in average water yield following salvage logging in Camp Creek, when the snow evaporation component of the model was turned off (i.e. windspeed = 0 m/sec). It appears that the snow evaporation component of the model is not applicable in this drainage as indicated by the small yield derived at increased windspeed. CFS-WRENSS was unable to predict the measured annual yield from Camp Creek, however, trends in yield predicted by the procedure were not significantly different than the measured yield changes following harvest. It must be remembered that WRENSS was designed "as a planning tool useful in evaluating the relative hydrologic impact of various management alternatives .....the strength of the procedure is in terms of estimating expected change" (Troendle & Leaf 1980).

TABLE 1 Paired basin and CFS-WRENSS predictions of water yield increases following timber removal from the Camp Creek watershed.

	Paired Basin Approach				CFS - WRENSS						
						Wind = 0			Wind = 3		
Water Year	Camp Creek Yield (MM) Actual	Camp Creek Yield (MM) Predicted	Diff (MM)	Percent Increase	Pre-harvest (MM)	Post-harvest (MM)	Diff (MM)	Percent Increase	Post-harvest (MM)	Diff (MM)	Percent Increase
65/66	78				133						
66/67	124				286						
67/68	139				250						
68/69		Missing data									
69/70	76				144						
70/71	164				325						
71/72	324				389						
72/73	81				110						
73/74	210				429						
74/75	161				343						
75/76	152				[illegible]						
76/77		Commencement of harvesting			74	77			75		
77/78	153	144	9	6.4%	308	321	13	4.2%	314	6	1.9%
78/79	109	87	22	25.2%	131	148	17	13.0%	144	13	9.0%
79/80	101	87	14	16.4%	159	178	19	11.9%	167	8	4.8%
80/81	131	85	46	53.9%	192	214	22	11.5%	197	5	2.5%
81/82	168	111	57	51.0%	279	305	26	9.3%	290	11	3.8%
82/83	169	151	18	11.9%	267	297	30	11.2%	282	15	5.3%
83/84	195	193	2	1.3%	223	245	22	9.9%	227	4	1.8%
84/85	111	92	19	20.6%	232	259	27	11.6%	242	10	4.1%
85/86	137	108	29	26.9%	274	303	29	10.6%	287	13	4.5%
Average			24	23.7%			23	10.4%		9	4.2%

CFS-WRENSS has been applied in several southern B.C. basins by Golding (1986, 1987) to evaluate the impact of various management options on streamflow. Similar use has been made by Bernier & Swanson (1986) on a pilot project set up to augment flows in Alberta. They simulated various cutting patterns on the basin to design an optimal cutblock size and pattern that would produce the maximum increase in yield. The results obtained in these studies illustrate the applicability of the CFS-WRENSS procedure to forest planning.

We recognize that we used the model in a way other than was actually intended, i.e. WRENSS was not designed to generate results that correspond to measured flows. This procedure was not intended to duplicate the environmental conditions occurring in a specific basin, as assumed in this project, since: 1) estimates of evapotranspiration (ET) were generated by another model known as WATBAL (Leaf & Brink 1973) based on empirical precipitation-ET relationships within several U.S. basins; 2) errors in translating available precipitation values to a study basin may occur; and 3) the difference in basin storage is assumed to be zero for the model. This would result in either under or overestimation of actual yield even though relative changes in yield following treatment may be accurately predicted.

CONCLUSIONS

Our results support the use of CFS-WRENSS in south central B.C., as an operational planning tool to assess harvesting alternatives on water yield. However, caution must be exercised due to the inherent limitations of this procedure. These results point to the need for research basins on a regional scale that provide the data necessary to check various models and to assess other hydrologic parameters upon which the models are built. Cheng *et al.* (1988) has presented the initial work in setting up an experimental basin for south central B.C. This basin should prove useful in evaluating models such as WRENSS. Work toward process oriented studies within this experimental basin would assist in refining the model and further determine the distribution of impacts on peak and low flows. Until such time as local research results become available the opportunistic use of hydrologic data is the best alternative available for assessing the impact of forest harvesting on the water resource.

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Difficulties of using basin approach to study the hydrology of wetlands

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ABSTRACT The extreme flatness of many of Canada's subarctic wetlands renders it difficult to delineate the drainage basin boundaries. This poses a problem to hydrological investigations that seek an understanding of the mechanism that water is transmitted through the wetlands.

In winter, only the narrow zones adjacent to the streams supply small quantities of groundwater while the remaining areas in the basin yield little runoff. In spring, rapid snowmelt and the blockage of the channels by snow and ice cause general flooding and water sweeps across the wetland irrespective of the drainage "divides". During summer, the wetland is covered by numerous puddles that coalesce or shrink according to the dictates of rainfall or evaporation. It is possible to monitor the amount of surface and subsurface flows which enter the feeder creeks during this period. The result shows the overwhelming contribution of overland flow.

It appears that the application of small basin concept to wetland hydrological research has to be modified to overcome the problems mentioned above.

RÉSUMÉ Le faible relief des terres humides subartiques canadiennes rend difficile l'établissement de lignes de partage entre les bassins. Ceci occasionne des problèmes lors de la conduite d'études hydrologiques visant à comprendre les mécanismes de transmission de l'eau à travers ces terres humides.

En hiver, les débits ne sont soutenus que par l'écoulement souterrain provenant de minces bandes de terre adjacentes aux ruisseaux. Au printemps, la fonte rapide et les embâcles engendrent une inondation généralisée, et l'eau s'écoule au travers des terres humides sans considération pour les lignes de "partage". En été, les terres humides sont recouvertes d'innombrables mares qui coalescent ou rétrécissent selon les régimes de précipitation. On peut mesurer à cette période les quantités d'écoulement de surface et souterrain qui arrivent aux ruisseaux principaux. Les résultats de ces mesures montrent une contribution prépondérante de l'écoulement de surface.

Il semble que les méthodes et concepts hydrologiques développés sur des petits bassins doivent être modifiés avant de pouvoir surmonter les problèmes mentionés ci-dessus.

INTRODUCTION

Drainage basins have long been regarded as natural hydrological entities, but the drainage divides can sometimes be difficult, if not impossible, to delineate on a topographical basis. Examples are karst terrains, areas fed by ice caps, or flatlands where water can move in different directions with the slightest change in the hydrological conditions. This research deals with one of these complications, concerning the flat and extensive wetlands of northern

Ontario, where the "basin" boundary changes drastically throughout the course of a year in response to the seasonal hydrological rhythm.

Many coastal rivers that empty into Hudson and James bays are fed by the vast wetlands where the regional gradient is 0.5 to 1 m km^{-1}. To understand the hydrological behaviour of these rivers, it is essential to study the mechanisms through which water is transmitted from the wetlands to the streams. One major pathway is for the water to be collected in feeder creeks which breach the levees and enter the main river. The conventional approach is to examine the small feeder creek basins so as to realise the amount of water supplied from the wetland to its rivers. A research project was undertaken to determine the mechanisms and magnitudes of water transfer. The difficulties of using a basin-study approach, and the partial solution to these problems are the foci of this paper.

STUDY AREA AND FIELD METHODS

The research "basin" (51° 08'N, 79° 48'W) is in subarctic Ontario near the coast of southern James Bay, west of the Harricanaw River (Fig.1). Mean January and July temperatures are about -20 and 15°C respectively, with the seasonal frost normally departing in mid-June and seldom returning until early September. Annual precipitation is 730 mm, of which about 30% is snowfall (Environment Canada, 1982).

The area has been uplifting since deglaciation. The extreme flatness in a humid climate has given rise to extensive wetlands, with belts of former raised beaches providing somewhat drier ground. Many rivers drain northward across the wetland. These rivers are joined by many short rills along their courses. One such creek was monitored intensely in 1985. The headwater of this creek is at the edges of marshy depressions. This creek flows along and then crosses a beach ridge until it discharges into the Waskhugaw River. The open marshes are covered by grasses, sedges, cattail and short shrubs, and the ridges are dominated by tall alder willows or by thick stands of black spruce.

A central meteorological site was set up to collect air temperature (using shielded thermistors), solar and net radiation (using Eppley and Middleton radiometers) and rainfall data (using Weathermeasure tipping-bucket rain gauge). A snow survey, carried out at the end of winter, using a method described by Adams (1976) provided total winter snow storage; and snowmelt was determined at several vegetated plots by measuring the rate of snow ablation, adjusted to snow surface density (Heron & Woo, 1978). Discharge data were gathered along the creek (Fig.1) using Leupold-Stevens type F recorders, with stage converted into discharge by empirically-derived equations. Groundwater wells were installed and the hydraulic conductivity determined using pumping tests. Overland flow was measured at several sites by funnelling the water from a measured width of the wetland towards a central weir. These collectors were made of eavestroughs or wooden sideboards, oriented perpendicularly to the surface flow lines. The deployment of instruments is shown in Fig.1.

FIELD PROBLEMS AND RESULTS

Based upon the hydrograph of wetland rivers, three natural seasons can be distinguished when the runoff generating processes and the quantity of flow production would vary. These include the winter low flow period, the spring freshet and the variable summer discharge that is mainly controlled by evaporation and rainfall. This study began in late winter and terminated at the end of summer, encountering several field problems pertaining to the

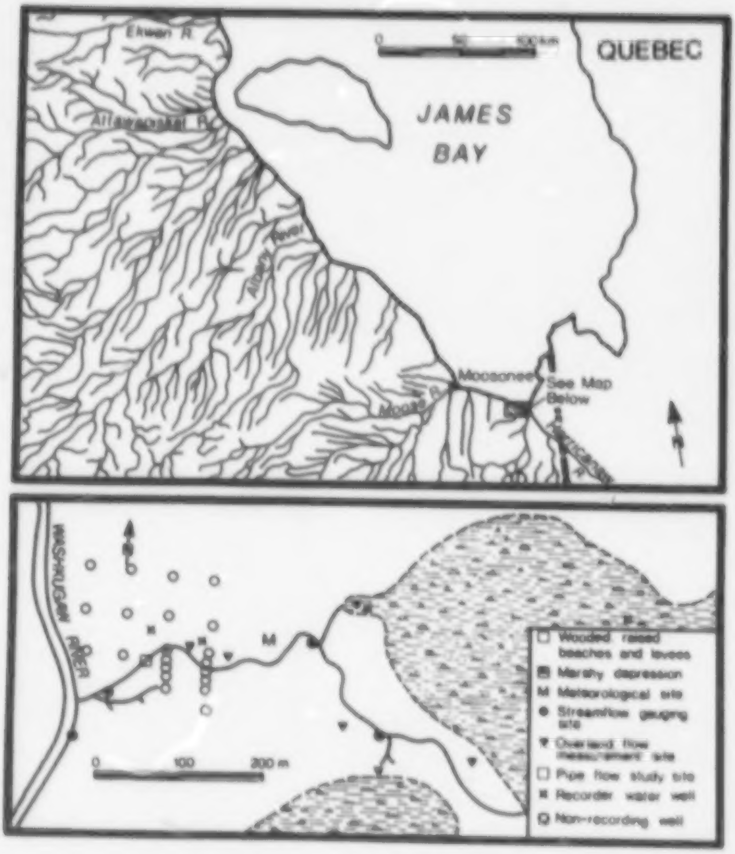
Ekwan R.
Attawapiskat R.
Albany River
Moose R.
Moosonee
See Map Below
JAMES BAY
QUEBEC
0 50 100 km
N
WASHKUGAN RIVER
M
0 100 200 m
☐ Wooded raised beaches and levees
▨ Marshy depression
M Meteorological site
● Streamflow gauging site
▼ Overland flow measurement site
☐ Pipe flow study site
✱ Recorder water well
○ Non-recording well

FIG.1 Location of study site and deployment of instruments.

drainage basin concept. By modifying the basin approach, however, we were successful to a large extent in meeting its objectives.

Winter study

In winter, the subarctic wetland developed a seasonal frost, the depth of which was controlled by the thickness of the insulating snow cover, which in turn was strongly influenced by the vegetation type. The rivers were covered with ice and snow and the feeder creeks ceased to flow. Under frozen conditions, only groundwater seepage remained active but the frost could alter the hydraulic head (Price & FitzGibbon, 1978) so that the local flow patterns were modified. Most of the groundwater flow did not reach the rivers, but along the banks where the hydraulic gradient increases, much icing was observed, bearing evidence that groundwater discharge to the rivers continued throughout winter. The Washkugaw River (drainage area 170 km^2) continued to flow at a rate of under 0.001 $m^3\ s^{-1}$ but a smaller, unnamed river, draining an area of 38 km^2, was totally dry. This contrasted with the larger discharge basins such as the Kwataboahegan (area 4250 km^2) which yielded an average winter flow of 2 $m^3\ s^{-1}$; or the North French (area 6680 km^2) with a mean winter discharge of 10 $m^3\ s^{-1}$ (Water Survey of Canada, 1985). It is likely that only the zone close to the river banks yielded sufficient groundwater to maintain winter flow, and the flow magnitude may be related to the extent of this zone rather than to the area of the drainage basins.

Spring study

Spring arrives with intense snowmelt, releasing the bulk of the entire winter snow accumulation within two to three weeks. The large meltwater release, together with frozen soil conditions, invariably leads to extensive surface flow across the flat wetland, and most of the runoff contribution to the rivers occurs as overland flow. In 1984 and 1985, surface flow on the coastal marsh initiated as localized pockets of runoff. The pattern was dictated by the disposition of the uneven snow cover and by the spatially variable source of meltwater supplies. Gradually, these pockets coalesced and there was concentrated flow along stream channels. At this time, the channels were filled with snow and ice, some of which blocked the flow to impound runoff behind snow dams or ice jams. Eventually, the impounded water overflowed the banks and the water moved from the rivers to the wetland. The small creeks which normally feed into the rivers became preferred conduits for the reversed flow, and the flood water was uninhibited by the raised beaches which normally form the inconspicuous drainage divides of the small basins. Details concerning the breakup situation have been described by Woo & Heron (1987) and Fig.2 shows the sequence of changing flow patterns during the 1985 breakup period.

It is evident that the basin approach is not applicable for studying water movement during the spring freshet. With the prevalence of overland flow it was virtually impossible to determine the runoff contribution from the wetland. Indeed, even streamflow gauging encountered great difficulties because of snow dams, ice jams and hazardous channel sections. Thus, information pertaining to the breakup period is limited to the direction of flow. On the other hand, by mapping the direction of water flow using dye, flotsam and other indicators, one realizes that the spring runoff contributing area has little resemblance to the "basin" that can be delineated on topographical maps. Mapping the flow paths offers useful information on the hydrological behaviour of the wetland, and leads to a better understanding of the complex flow relationship between the wetland and its rivers during breakup.

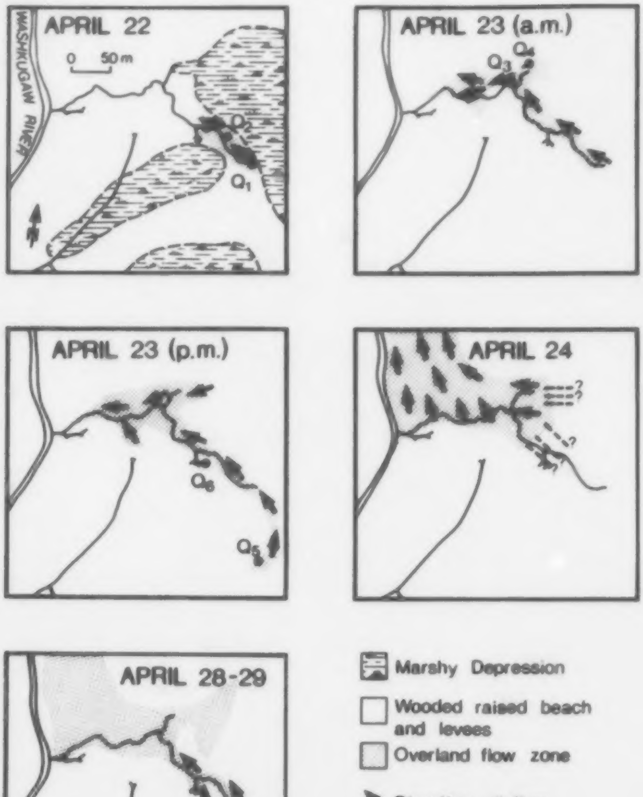
APRIL 22
WASHKUGAW RIVER
0 50 m
Q2
Q1
APRIL 23 (a.m.)
Q3
Q4
APRIL 23 (p.m.)
Q6
Q5
APRIL 24
?
?
?
?
APRIL 28-29
Marshy Depression
Wooded raised beach and levees
Overland flow zone
Direction of flow
Stream channel in snow-free period

FIG.2 Sequence of breakup at the study "basin" and its surrounding area during the spring of 1985. Note that surface flows were not confined by the topographical divides.

Summer study

Summer is the time when the basin concept appears to be the most appropriate because most the wetland runoff is channelled into the feeder creeks that enter the main rivers. However, it is exceedingly difficult to define the drainage boundary for the wetlands. Additionally, field observations revealed that because of the low drainage divides, a rising water table could expand the "basin" area to capture the water that otherwise moved to the adjacent areas; or would tap the rather stagnant water held in the depressions. An alternative research approach is to determine the type and amount of water which is delivered from the wetland into the feeder creeks along the lengths of their channels. The findings should provide information on the manner in which water moves into the creeks, and the temporal changes in the magnitude of flow.

One segment of a feeder creek was used for this experimental study. Three types of flows were determined including Darcian groundwater flow, pipeflow within the soil (Woo & diCenzo, 1988) and overland flow directly from the wetland. The inflow and outflow for a control segment of the creek were also gauged. Evaporation from the stream water surface was computed using the Priestley and Taylor model (Roulet & Woo, 1986) and direct rainfall onto the creek was measured. Through the following water balance relationship, the contribution from different sources of wetland drainage can be estimated:

$$Q_o - Q_i = P - E + Q_g + Q_p + Q_s$$

where Q_o and Q_i are storm outflow and storm inflow from the segment, P is direct rainfall, E is evaporation from the water surface, Q_g, Q_p and Q_s are groundwater, pipeflow and overland flow. Over the period of a storm, the net change in storage in the channel is considered to be negligible.

The storm of June 8-23 1985 illustrates the relative contribution from various sources (Fig.3). Storm inflow and storm outflow were obtained by baseflow separation from the streamflow hydrographs. Results of the water balance showed that overland flow was the overwhelming process through which water was delivered to the channel, accounting for 89% of the storm runoff generated within the study reach. Pipeflow provided about 10% while channel precipitation accounted for 2% of streamflow. Channel evaporation loss was insignificant (-1%) as was groundwater flow (0.1%). This demonstrates that wetland discharges the bulk of its storm water to the streams through surface runoff. During the drier periods, the surface depression areas shrank as the water table receded, and the effective runoff contributing area diminished also. It is impossible to map the changing areas on the wetland that supported surface flow, but it is possible to use the channel banks as the reference strip for monitoring the temporal changes of water input into the feeder streams.

CONCLUSIONS

This study yielded two sets of conclusions, one being substantive, the other methodological in nature. In terms of substantive findings, it was found that there is little interaction between the wetland and its streams in winter, other than a minor amount of groundwater discharge to sustain baseflow and to form icing in the rivers. During the thawed season, the linkages between the wetland, the small creeks that feed the larger rivers, and the wetland rivers themselves can be summarized by Fig.4. In spring, snowmelt is the major input to the wetland and the meltwater released quickly exceeds wetland storage. Overland flow dominates as rills and creeks are choked with snow and ice up to

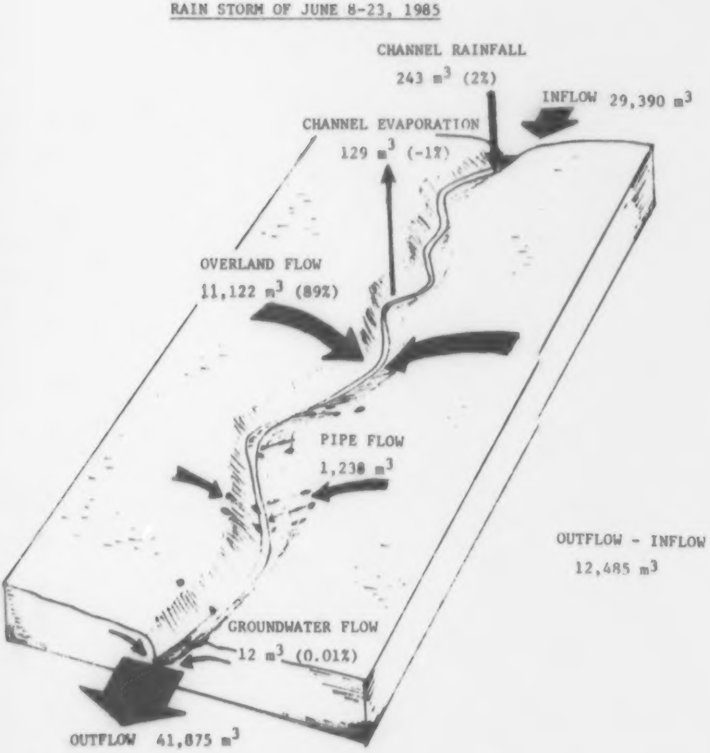
RAIN STORM OF JUNE 8-23, 1985
CHANNEL RAINFALL
243 m³ (2%)
INFLOW 29,390 m³
CHANNEL EVAPORATION
129 m³ (-1%)
OVERLAND FLOW
11,122 m³ (89%)
PIPE FLOW
1,238 m³
OUTFLOW - INFLOW
12,485 m³
GROUNDWATER FLOW
12 m³ (0.01%)
OUTFLOW 41,875 m³

FIG.3 Contribution from various water sources to the flow in a small wetland creek during the storm of June 8-23, 1985.

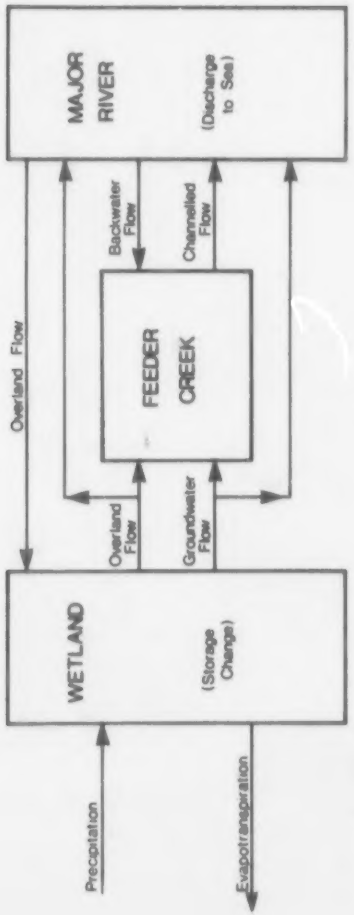
MAJOR
RIVER
(Discharge to Sea)
Overland Flow
Backwater Flow
Channelled Flow
FEEDER
CREEK
Overland Flow
Groundwater Flow
WETLAND
(Storage Change)
Precipitation
Evapotranspiration

FIG.4 Conceptualised linkages between the wetland, the feeder creeks and the main rivers.

the bankful level. At a later stage of breakup, backwater flooding of rivers by snow and ice jams may push the water back to the wetland, to be discharged through some low points along the banks downstream. Groundwater flux is a source of baseflow but is relatively unimportant because the wetland surface remains frozen. In summer, the wetland gains water from rainfall, and loses water to evaporation, to overland flow and to groundwater discharge that enters the feeder creeks. These feeders then concentrate much of the flow to provide a link between the wetland and the rivers.

Methodologically, the basin concept was found to be inappropriate for this wetland study because in winter, only the zone adjacent to the river banks yielded some water to the streams. The extent of this zone is more a function of the stream length than the total basin area. In spring, no basin divide can be a barrier to overland flow as the large volume of meltwater from the wetland and the floodwater from the rivers sweep across the flat terrain, following all the low points created by the topography and by the ablating snow and ice cover. At this time of the year, only the flow direction can be mapped by tedious and sometimes dangerous fieldwork, but as yet, no better method has been devised to overcome the problem. In summer, emphasis may be shifted from an areal (basin) to a linear (streambank) approach. By examining the wetland flow contribution along the length of the banks from different sources, the magnitude of wetland input to its rivers can be obtained.

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An application of the geomorphological unit hydrograph theory to an experimental watershed

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ABSTRACT In the early nineteen seventies the Trzebunka River experimental watershed was established and operated by the Technical University of Cracow, Poland. The main purpose of this facility is to: test various mathematical models of the watershed, develop and test an automatic data acquisition system, perform detailed and often unique measurements of various hydrological processes, and provide field experience for university students. In this paper a research project is described which was carried out at the experimental watershed to analyze rainfall-runoff relations using the geomorphologic unit hydrograph theory.

RÉSUMÉ Au début des années '70, l'Université Technique de Cracovie, Pologne, mit sur pied le bassin expérimental de la rivière Trzebunka. Les principaux objectifs de cette installation sont de tester différents modèles mathématiques du bassin, de développer et de tester différents systèmes automatiques d'acquisition de données, d'effectuer des mesures détaillées et souvent uniques des processus hydrologiques, et de fournir une expérience de terrain aux étudiants. Cette communication décrit une étude menée sur le bassin, et où les relations précipitations:débits ont été analysées en se servant de la théorie géomorphologique de l'hydrogramme unitaire.

INTRODUCTION

The establishment of the Trzebunka experimental watershed coincided with plans to build a flood control reservoir located at Dobczyce on the Raba River. In order to establish an efficient real time flood control system for the reservoir it was essential to develop an appropriate mathematical model of the watershed along with a precise automatic data acquisition program on various hydrometeorological variables.

In addition, many research projects were initiated to develop and test mathematical models, to establish a reliable automatic data acquisition system, and to perform detailed observations of various hydrological processes in the catchment.

One of the research projects was to study various models of rainfall-runoff relation, including the instantaneous unit hydrograph (IUH) derived based on the geomorphologic theory.

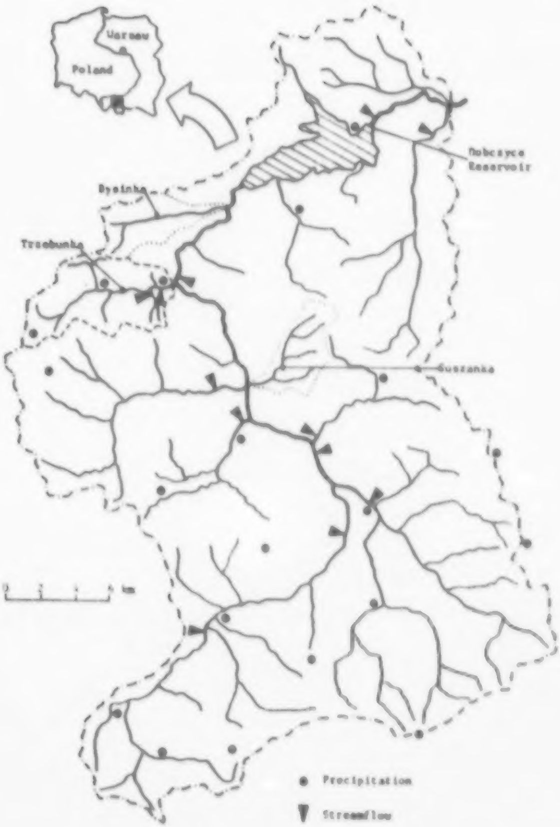

Warsaw
Poland
Dobczyce Reservoir
Bysinka
Trzebunka
Suszanka
0 2 4 6 km
● Precipitation
▼ Streamflow

FIG.1 Watershed of the Raba river, Poland.

DESCRIPTION OF THE BASIN

The Trzebunka River experimental watershed (area 3,038 km^2) is a tributary of the Raba River (area 630 km^2), which in turn drains into the Vistula River, and hence into the Baltic Sea. Its location in Poland is shown in Fig.1. The watershed is located in the foothills of the Karpaty Mountains, with an average elevation ranging from about 1000 to 1310 m above sea level. The entire basin is characterized by high hills with steep slopes. Higher elevations are bare or covered with mixed forest, whereas lower elevations are used for agriculture (mainly to grow rye, oats, and potatoes) and for animal grazing (mainly sheep). There is no heavy industry, but the area is extensively used for recreation owing to the specific microclimate, mineral water springs (health spas), and beautiful scenery. Due to the climate characteristics, topography, and geology, the streams have large floods with very high velocities.

EXPERIMENTAL WATERSHED

The Trzebunka experimental watershed has been in operation over ten years, and there are now five permanent technicians employed. The research is managed by the University faculty members, and the facility is also used by other government organizations.

Recently, an international conference on "Hydrological Processes in the Catchment" (1986) was held in Cracow in conjunction with the various activities related to the experimental watershed.

An especially intensive research effort has recently been concentrated on measuring and studying the interception process. For that purpose, raingauges were installed in a very dense square grid mesh over a small area (some gauges were placed under trees, others in an open area); a system of lined troughs was installed to collect surface runoff; special rubber troughs were wrapped around trees to collect throughflow, and a small watershed was covered with impervious material to collect surface runoff. Very detailed observations were carried out on trees which were cut before a storm, and the variability of interception with time was studied by the automated data acquisition system.

Evapotranspiration has also been intensively studied and modelled. In addition, extensive observations are conducted on the infiltration process, soil moisture, and groundwater fluctuations. Other hydrometeorological parameters measured as well are river flow, snowmelt, wind velocity, temperature, etc. Most of the observations are obtained in continuous time by automatic data acquisition system.

AUTOMATIC DATA ACQUISITION SYSTEM

The on-site microprocessor controlled data acquisition system was developed and installed in order to acquire, process, store, and if required, transmit data. A diagram of the system is shown schematically in Fig.2. The system consists of string sensors C_1, C_2, C_n (to measure parameters such as precipitation, temperature, humidity, wind speed and direction, water level, soil moisture, evapotranspiration, etc.), connected to a microprocessor controller with memory, which is interfaced with the IBM PC computer for data storage.

Both hardware and software designs were time consuming, but the experience gained proved that the operational procedure is very reliable and extremely useful. Over ten years of data is now available on many hydrometeorological parameters obtained from a very dense network.

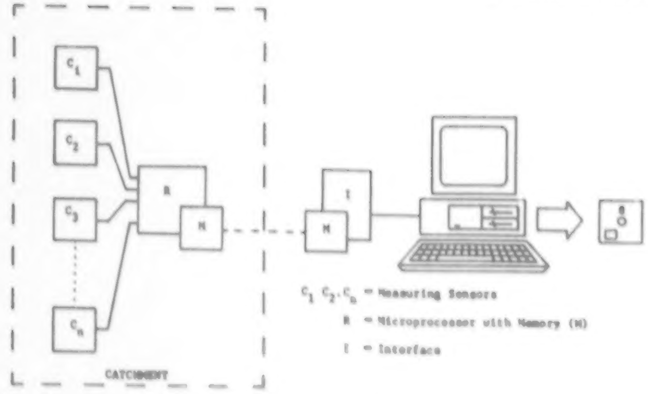

C_1
C_2
C_3
C_n
R
M
M
I
CATCHMENT
C_1 C_2, C_n = Measuring Sensors
R = Microprocessor with Memory (M)
I = Interface

FIG.2 Automatic data acquisition system.

MATHEMATICAL MODEL

In order to obtain a real-time flow forecasting model as an input to the Dobczyce reservoir for its design and operation, several mathematical models of the watershed were developed and tested. A kinematic watershed model was developed which consists of the following elements:

(a) Total precipitation input was derived and its time-space-direction characteristics were modelled by kinematic equations.

(b) Excess rainfall for each sub-watershed was estimated by several methods, including Guillot and Dubond (1979), given by:

$$N(t) = R(t) - B_1 [1 - \exp (\frac{-P(t)}{B_1})] \tag{1}$$

where N(t) is the excess rainfall, R(t) is the total precipitation, and B_1 is the retention parameter.

(c) The excess rainfall-runoff relationship was described by several models including the Nash linear model given by:

$$(Q(t) (K\frac{d}{dt} + 1)^N = N(t) \tag{2}$$

where K and N are parameters. Also, a nonlinear relationship was used (Stephenson & Meadows, 1986) and is given by:

$$\frac{k_1}{Q(t) + k_2} \frac{dQ}{dt} + Q(t) = N(t) \tag{3}$$

where k_1 and k_2 are parameters. As an alternative for rainfall-runoff relations the geomorphological unit hydrograph was developed.

(d) The hydrograph was computed based on one-dimensional kinematic operations for flow given by:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q_L \tag{4}$$

and

$$q = \alpha y^m \tag{5}$$

where Q is the flow rate ($m^3 s^{-1}$), A is the cross sectional area (m^2), t is time (sec), x is the space axis (m), q is the average discharge across a section per unit width ($m^2 s^{-1}$), y is the depth of water (m) and α, m are coefficients dependent on surface roughness and bed slope.

The numerical solution details and the applications of models will not be presented further in this article.

In the model outlined above, an alternative subroutine is also investigated to derive the rainfall-runoff relationship by the geomorphological unit hydrograph, and is presented in the next section.

A RAINFALL-RUNOFF ANALYSIS BY THE GEOMORPHOLOGIC IUH

Description of theory

Rodriguez-Iturbe and Valdes (1979) linked, in an analytical fashion, the hydrologic response of a catchment represented by the instantaneous unit hydrograph (IUH) with the geomorphologic characteristics of the watershed.

Following the hypothesis of the geomorphologic IUH (GUH), for a basin of order W, the formulation of GUH can be expressed as (Rosso, 1984):

$$g(t) = (a_w t + b_w)\exp(-2vL^{-1}t) + \sum_{i=1}^{w-1} b_i \exp(-2vL^{-1}tR_L^{w-i}) \tag{6}$$

where

$g(t)$ = geomorphologic IUH or GUH
v = mean streamflow velocity
L = mean length of higher order stream
a_w = functions of R_A, R_B, R_L, λ_i, λ_w
b_i = functions of R_A, R_B, R_L, λ_i
R_A, R_B, R_L = area, bifurcation, and length ratios, respectively
λ_i = inverse mean waiting time in ith order stream equal to vL_i^{-1}
λ_w = modified higher order inverse mean waiting time, and
L_i = mean length of ith order stream

The application of equation (6) to real watersheds is cumbersome; therefore, alternative relationships were derived based on regression and are given by:

$$q_p = 0.364\ R_L^{0.43}\ vL^{-1} \tag{7}$$

$$t_p = 1.58\ (R_B/R_A)^{0.55}\ R_L^{-0.38}\ v^{-1}L \tag{8}$$

where q_p is the peak flow, t_p is the time to peak, and the remaining parameters are previously defined.

By multiplying equations (7) and (8), the dimensionless product $G = q_p t_p$ is obtained:

$$G = 0.58\ (R_B/R_A)^{0.55}\ R_L^{0.05} \tag{9}$$

Within the framework of the GUH model, the velocity v is given by the following relationship:

$$v = 0.665\ \alpha_\Omega^{0.6}\ (0.1 \times I_r \times A_\Omega)^{0.4} \tag{10}$$

where I_r is the intensity of the excess rainfall, and A_Ω is the area of the highest order catchment.

The parameter α_Ω relates the velocity to the channel characteristics, which for a rectangular channel is given by:

$$\alpha_\Omega = S^{1/2}/n \times b^{2/3} \tag{11}$$

where S, n and b are the slope of the channel, Manning's roughness coefficient and the width of the channel, respectively.

Utilising the GUH theory for the calculation of the runoff hydrograph for ungauged watersheds, for which neither discharge nor stage data are available, it is necessary then to utilise equation (11).

The Nash model of IUH can also be parameterised following the geomorphologic model of catchment response. The Nash model is given by:

$$IUH(t) = [k\ \Gamma\ (N)]^{-1}\ (t/k)^{N-1}\ \exp\ (-t/k) \tag{12}$$

where the values of Nash's parameters in terms of GUH theory are (Rosso, 1984):

$$N = 3.29\ (R_B/R_A)^{0.78}\ R_L^{0.07} \tag{13}$$

and

$$k = 0.70\ [R_A/(R_B\ R_L)]^{0.48}\ v^{-1}L \tag{14}$$

where the parameters are as previously defined.

The rainfall-runoff relations based on GUH theory were applied to gauged and ungauged small watersheds, and the results are presented in the next section.

Applications of GUH

The GUH was at first developed for the gauged Trzebunka River experimental watershed. The value of the parameters are given in Table 1. The comparison of observed and predicted discharge by the GUH model are shown on Fig.3, indicating good agreement.

Fig.4 shows a comparison between hydrographs obtained from the GUH theory and the Nash IUH model. The results demonstrate close agreement between the hydrographs. The model parameters are physically meaningful and easily determined quantities.

The sensitivity of the GUH hydrographs to changes in the values of parameters (Table 1) is relatively insignificant as can be seen in Fig.5. This observation supports the application of GUH theory to ungauged watersheds.

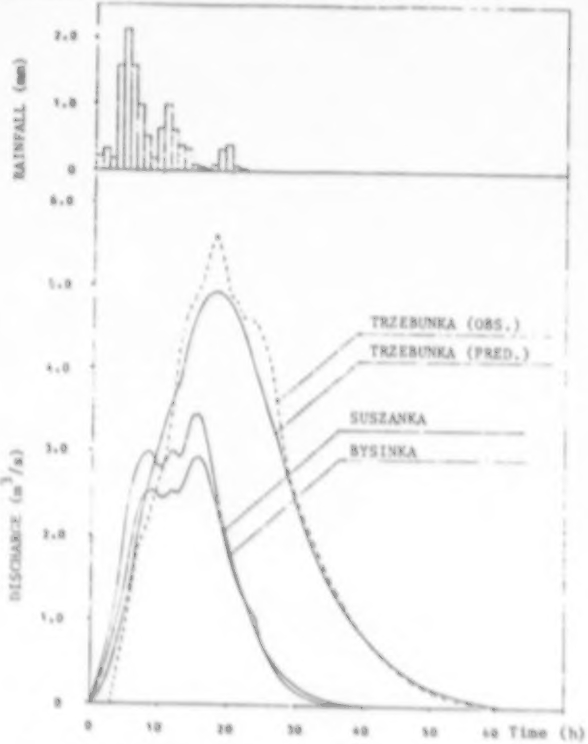


FIG.3 Computed hydrographs for Trzebunka (guaged), Suszanka and Bysinka (unguaged) rivers.

where the parameters need to be estimated. Therefore, the rainfall-runoff relations for the two ungauged watersheds (Suszanka and Bysinka) were derived based on the parameters (Table 1) derived from the topographic map, and plotted in Fig.3.

Based on the results of this study it can be concluded that the GUH theory provides an attractive alternative to purely empirical rainfall-runoff relations.

CONCLUSIONS

The Trzebunka experimental watershed is a very valuable field research facility. It is used as a test site for new measurement techniques, and for conducting many often unique hydrological observations; the available observational data is used to test, calibrate, and validate mathematical models. The watershed is used extensively for educational purposes by the University.

The theory of the geomorphological unit hydrograph was tested at gauged and ungauged sub-watersheds. The results indicate that the GUH catchment response can be described by a physically meaningful and easily determined parameters.

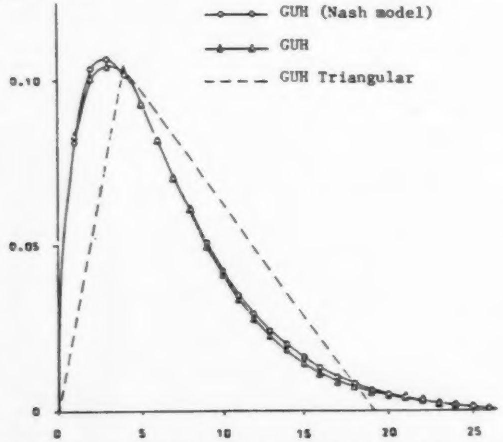
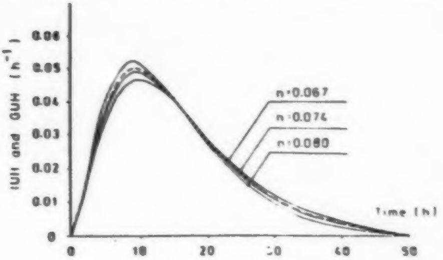


FIG. 4 Comparison between geomorphological instantaneous unit hydrographs for Suszanka river.

TABLE 1 Geomorphological characteristics of analysed basins and parameters for kinematic wave: B=channel width; S=channel slope; I_1=rainfall intensity; n=Manning's roughness coefficient.

Basin	*Area*	*Length*	*Horton's order ratios*			*B*	*S*	I_1	*n*
	(km²)	*(km)*	R_B	R_L	R_A	*(m)*	*%*	mm h^{-1}	
Trzebunka	*30.38*	*10.7*	*4.56*	*2.45*	*4.82*	*10*	*0.0065*	*0.481*	*0.067*
Suszanka	*15.64*	*7.4*	*3.88*	*3.63*	*5.39*	*8*	*0.0253*	*0.481*	*0.067*
Bysinka	*13.51*	*8.1*	*3.83*	*3.00*	*4.73*	*3*	*0.0155*	*0.481*	*0.067*



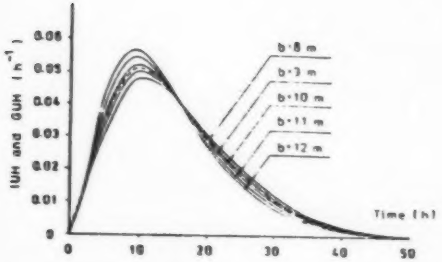


FIG. 5 Comparison of IUH (dotted line) and GUH (solid line) for various Manning's roughness coefficients (upper graph) and varying channel width (lower graph).

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